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TOXICITY STUDIES WITH ARSENIC IN EIGHTY CALIFORNIA SOILS[1, 2]

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INTRODUCTION

THE INCREASING USE of arsenic in herbicides, insecticides, and soil sterilants presents problems of great economic importance. The farmer, needing practical methods for controlling pests, seeks the cheapest and most effective reagents, whereas the soils investigator must try to conserve our agricultural areas for present and future generations.

Arsenic, being cheap, readily available, and extremely toxic, is in constant demand for weed and insect-pest control and is recommended by many companies, often without specific knowledge of dosages required, effective methods of application, or ultimate effects upon the soil.

In the field use of arsenic, workers naturally ask what form is most effective for the particular type of treatment being used, how much will be needed for the desired results, and how long the results will last. The soils investigator wants to know what the effects of long-time accumulation of arsenicals in soils will be, whether the soil is permanently harmed when crop yields have been reduced, and how one may remove or remedy the toxic condition resulting from arsenic in the soil.

A previous publication (*6*)[5] presented data on arsenic toxicity[6] in four

[1] Received for publication January 17, 1938.

[2] This paper was made possible by the coöperative project on control of noxious weeds conducted by the California Agricultural Experiment Station and the Division of Cereal Crops and Diseases, Bureau of Plant Industry, United States Department of Agriculture.

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[5] Italic numbers in parentheses refer to "Literature Cited" at the end of this paper.

[6] The term "toxicity" has acquired a wide variety of meanings. For purposes of the present group of papers (*7, 8, 13*) the criterion adopted is the application of chemical causing an almost complete suppression of growth. This use of the word has developed because in the control of weeds the practical object is to inhibit development completely.

TABLE 1

CHARACTERISTICS OF CALIFORNIA SOILS USED IN TOXICITY SERIES*
(All samples from surface 4 inches)

No.	Soil type	Origin	Mode of formation	Stage of development	Color	Remarks†	Moisture content of cultures	Soil used in each culture
				Sands				
							per cent	*gm*
1	Holland loamy gravelly sand	Acid igneous	Primary	Immature	Brown	Slightly acid	12.8	500
2	Niland gravelly sand	Mixed	Secondary alluvial	Youthful	Light brown-gray	Calcareous; saline	10.0	500
3	*Oakley sand*	*Mixed*	*Secondary aeolian*	*Youthful*	*Light brown*	Slightly acid	6.5	600
4	Rositas fine sand	Mixed	Secondary alluvial	Recent	Light brown-gray	Alkali; calcareous	14.5	500
5	*Superstition gravelly sand*	*Mixed*	Secondary alluvial	Youthful	Light gray	Calcareous	12.4	500
6	Tujunga sand	Acid igneous	Secondary alluvial	Recent	Light brown-gray	Neutral	12.3	500
				Gravelly and sandy loams				
							per cent	*gm*
7	Aiken gravelly loam	Basic igneous	Primary	Semimature	Red	Slightly acid	13.3	500
8	Arbuckle gravelly sandy loam	Sedimentary	Secondary alluvial	Youthful	Brown	Neutral	10.0	500
9	Chualar fine sandy loam	Acid igneous	Secondary alluvial	Immature	Dark brown	Neutral	13.0	600
10	Columbia fine sandy loam	Mixed	Secondary alluvial	Recent	Light gray-brown	Neutral	18.0	500
11	Corning gravelly loam	Mixed	Secondary alluvial	Semimature	Brown-red	Moderately acid	12.2	500
12	Delano fine sandy loam	Acid igneous	Secondary alluvial	Immature	Light red-brown	Basic	15.0	600
13	Foster fine sandy loam	Acid igneous	Secondary alluvial	Recent	Dark brown-gray	Neutral	16.2	500
14	Fresno sandy loam‡	*Acid igneous*	*Secondary alluvial*	*Mature*	*Brown-gray*	Alkaline	15.0	600
15	Greenfield coarse sandy loam	Acid igneous	Secondary alluvial	Youthful	Brown	Neutral	15.0	600
16	Hanford sandy loam	Acid igneous	Secondary alluvial	Recent	Light brown	Neutral	14.0	500
17	Hanford fine sandy loam	Acid igneous	Secondary alluvial	Recent	Light brown	Neutral	13.8	500
18	Meloland fine sandy loam	Mixed	Secondary alluvial	Recent	*Light gray-brown*	*Alkali; calcareous*	13.3	500
19	Merced fine sandy loam	Acid igneous	Secondary alluvial	Semimature	Dark gray	Neutral	15.6	500
20	Oakdale coarse sandy loam	Acid igneous	Secondary alluvial	Recent	Gray-brown	Neutral	10.8	600
21	Ramona sandy loam	Acid igneous	Secondary alluvial	Immature	Brown	Neutral	10.7	500
22	Redding gravelly loam	Mixed	Secondary alluvial	Mature	Brown-red	Moderately acid	13.3	500
23	Rocklin sandy loam	Acid igneous	Secondary alluvial	Mature	Brown-red	Slightly acid	17.9	500
24	Salinas fine sandy loam	Mixed	Secondary alluvial	Immature	Dark brown-gray	Neutral	14.4	500
25	Sierra gravelly loam	Acid igneous	Primary	Semimature	Brown-red	Moderately acid	12.5	500
26	Sierra sandy loam	Acid igneous	Primary	Semimature	Brown-red	Moderately acid	13.5	500
27	Sites fine sandy loam	Sedimentary	Primary	Semimature	Brown-red	Moderately acid	12.0	500
28	Tulare fine sandy loam	Mixed	Secondary alluvial	Immature	Light gray	Calcareous	20.0	500
29	*Yolo fine sandy loam*	*Sedimentary*	Secondary alluvial	Recent	Brown	Neutral	15.0	500

	Loams							
							per cent	*gm*
30	Egbert loam	Mixed organic	Secondary alluvial	Immature	Dark gray	Slightly acid	32.0	500
31	Farwell loam	Basic igneous	Secondary alluvial	Youthful	Chocolate-brown	Neutral	17.6	500
32	Gridley loam	Basic igneous	Secondary alluvial	Semimature	Brown	Slightly acid	22.1	500
33	Honcut loam	Basic igneous	Secondary alluvial	Recent	Red-brown	Slightly acid	21.4	500
34	Madera loam	Acid igneous	Secondary alluvial	Mature	Brown	Neutral	12.0	500
35	Panoche light loam	Sedimentary	Secondary alluvial	Recent	Brown-gray	Calcareous	14.0	500
36	Pinole loam	Sedimentary	Secondary alluvial	Immature	Yellow-brown	Slightly acid	15.0	500
37	Placentia light loam	Acid igneous	Secondary alluvial	Semimature	Brown-red	Neutral	10.4	500
38	Pleasanton loam	Sedimentary	Secondary alluvial	Immature	Brown	Neutral	16.7	500
39	Pond heavy loam	Acid igneous	Secondary alluvial	Immature	Brown-gray	Alkaline; calcareous	11.7	500
40	San Joaquin loam	Acid igneous	Secondary alluvial	Mature	Brown-red	Moderately acid	21.0	500
41	Tehama loam	Mixed	Secondary alluvial	Immature	Light yellow-brown	Neutral	13.6	500
42	Vina loam	Basic igneous	Secondary alluvial	Recent	Brown	Neutral	22.5	500
43	Yolo loam	Sedimentary	Secondary alluvial	Recent	Brown	Neutral	20.1	500
	Silt and clay loams							
							per cent	*gm*
44	Aiken clay loam	Basic igneous	Primary	Semimature	Red	Slightly acid	21.3	400
45	Antioch clay loam	Sedimentary	Secondary alluvial	Mature	Dark brown	Moderately acid	15.8	600
46	Arbuckle clay loam	Sedimentary	Secondary alluvial	Recent	Brown	Neutral	18.5	500
47	Chino silty clay loam	Acid igneous	Secondary alluvial	Youthful	Dark gray	Neutral	20.4	500
48	Columbia silty clay loam	Mixed	Secondary alluvial	Recent	Light gray-brown	Neutral	26.0	500
49	Mariposa silt loam	Sedimentary	Primary	Semimature	Brown-yellow	Moderately acid	20.0	500
50	Marvin silty clay loam	Mixed	Secondary alluvial	Immature	Light brown	Neutral	24.4	500
51	Ramada silt loam	Mixed	Secondary alluvial	Recent	Light yellow-brown	Neutral	19.7	500
52	Sacramento clay loam	Mixed	Secondary alluvial	Immature	Dark gray	Slightly acid	28.2	400
53	Yolo silt loam	Sedimentary	Secondary alluvial	Recent	Brown	Neutral	18.1	500
54a	Yolo clay loam§	Sedimentary	Secondary alluvial	Recent	Brown	Neutral	30.0	500
54b	Yolo clay loam§	Sedimentary	Secondary alluvial	Recent	Brown	Neutral	30.0	500

* Information from (*14*, *15*, and *16*).
† Data given in this column were taken from (*14*, *15*, and *16*). They apply to the soil types in general. No such determinations were made on the samples collected.
‡ The Fresno sandy loam used in this and in previous tests is designated as brown phase. Shaw now classifies this soil in the Dinuba series (*14*).
§ Soil 54a harvested December 22, 1934; soil 54b harvested June 4, 1935.

(Table concluded on next page.)

TABLE 1—(*Concluded*)

No.	Soil type	Origin	Mode of formation	Stage of *development*	Color	Remarks†	Moisture content *of cultures*	Soil used in each culture
				Clays				
							per cent	*gm*
55	Alamo adobe clay	Mixed	Secondary alluvial	Mature	Dark gray	Neutral	27.3	500
56	Anita adobe clay	Basic igneous	Secondary alluvial	Immature	Dark brown	Neutral	26.3	500
57	Capay adobe clay	Sedimentary	Secondary alluvial	Immature	Gray-brown	Neutral	27.9	500
58	Clear Lake adobe clay	Sedimentary	Secondary alluvial	Youthful	Gray-black	Neutral	24.4	500
59	Conejo adobe clay	Basic igneous	Secondary alluvial	Recent	Gray-black	Neutral	29.2	500
60	Diablo adobe clay	Sedimentary	*Primary*	Semimature	Gray-black	Neutral	33.1	500
61	Dublin adobe clay	Sedimentary	Secondary alluvial	Recent	Gray-black	Neutral	33.7	500
62	Dunnigan clay	Mixed	Secondary alluvial	Semimature	Brown-gray	Saline	28.0	500
63	Esparto clay	Sedimentary	Secondary alluvial	Youthful	Light brown	*Slightly acid*	22.4	500
64	Farwell adobe clay	Basic igneous	Secondary alluvial	Youthful	Chocolate-brown	Neutral	25.3	500
65	Fresno *light* clay	*Acid igneous*	Secondary alluvial	Mature	Brown-gray	Alkaline	28.0	500
66	Imperial clay	Mixed	Secondary alluvial	Recent	Light gray	Alkali	28.8	500
67	Landlow adobe clay	Basic igneous	Secondary alluvial	Mature	Dark brown	Calcareous subsoil	32.1	500
68	Madera clay	Acid igneous	Secondary alluvial	Mature	Brown	Neutral	25.0	500
69	Merced adobe clay	Acid igneous	Secondary alluvial	Semimature	Black	Neutral	49.1	500
70	*Montezuma adobe clay*	Sedimentary	Secondary alluvial	Semimature	Gray-black	Neutral	28.0	500
71	Montezuma adobe clay	Sedimentary	Secondary alluvial	Semimature	Gray-black	Neutral	33.0	500
72	Panoche adobe clay	Sedimentary	Secondary alluvial	Recent	Brown-gray	Calcareous	25.0	500
73	Porterville adobe clay	Basic igneous	Secondary alluvial	*Immature*	Chocolate-brown	Neutral	26.5	500
74	Salinas clay	Mixed	Secondary alluvial	Immature	Dark brown-gray	Neutral	30.0	500
75	Sites adobe clay	Sedimentary	Primary	Semimature	Red-brown	Moderately acid	22.5	500
76	Stockton adobe clay	Basic igneous	Secondary alluvial	Mature	Gray-black	Basic	32.0	500
77	Tulare clay	Mixed	Secondary alluvial	Immature	Light gray	Calcareous	28.0	500
78	Willows adobe clay	*Sedimentary*	*Secondary alluvial*	Semimature	Dark brown	Neutral	30.5	500
79	Yolo adobe clay	Sedimentary	Secondary alluvial	Recent	Brown	Neutral	26.6	500
80	Yolo clay	Sedimentary	Secondary alluvial	Recent	Brown	Neutral	26.3	500

† Data given in this column were taken from (*14*, *15*, and *16*). They apply to the soil types in general. No such determinations were made on the samples collected.

California soils. The range of concentrations used in these early trials was not sufficient to show what changes in toxicity take place with repeated cropping; furthermore, two of the soils used were not quite typical. The Stockton adobe clay for the first experiment was taken near a drainage ditch and proved to be mostly subsoil that behaved anomalously. The Columbia fine sandy loam was not so fertile and was coarser-textured than that used in later tests. A retest was therefore devised to correct these difficulties.

When the results, which are presented in a later section, were compared with those of the previous experiment, it was impossible to formulate general relations between toxicity and soil type suitable for prescribing dosages. Therefore a simpler test was devised that could be used simultaneously on many soils. The results of these simple comparative tests form the main subject of this report

MATERIALS AND METHODS

Selection and Sampling of Soils.—In conjunction with the Division of Soil Technology at Davis, sampling areas for type soils were located on soil-survey maps. The samples, taken from the top 4 inches after removal of the surface débris, were collected during the summer dry season, and wherever possible, near fence lines or from similar locations where they had not recently been disturbed.

After transportation to Davis, they were pulverized to pass a ¼-inch screen and were stored in burlap bags in a dry place until used. Table 1 presents descriptive data obtained from various sources (*14, 15, 16*). A casual survey will indicate the wide variety tested. Collected throughout the length and breadth of the state, the soils illustrate almost every textural grade, mode of formation, color, and reaction; and most important agricultural soils are represented by one or more types.

Biological Testing of Toxicity.—The biological testing method used in studying arsenic toxicity in these soils has been described (*6, 9*). It consists of growing a series of cultures in No. 2 cans in the greenhouse. The air-dry soils are weighed into the cans, which have been tared, bits of coarse gravel being added to bring them to a standard weight. The arsenic is added in solution in the water used to bring the soils to field capacity. Dry soil and solution are rapidly mixed, each in 3 successive portions to insure uniform distribution. After moistening, 13 Kanota oat seeds are planted in each can; and wrapping paper is laid over the cultures to prevent drying. The paper is removed as soon as the seeds germinate, and the plants are thinned to 10 at the end of the first week of growth. There-

after, they are watered as required by growth, sunshine, and humidity. After 30 days, they are cut off at the soil level. The fresh weights of the tops are recorded, and are used as a measure of toxicity of the arsenic applied.

The stock arsenic solution is prepared by mixing 4 parts of screened, dry, arsenic trioxide, 1 part of C.P. stick caustic soda, and 3 parts of water. When heated slightly, this mixture goes into solution, giving a clear sirupy liquid containing 50 per cent As_2O_3 by weight. The diluted solution for application to the soils is prepared by making up 10 grams of this to a liter. The resulting solution, containing 5,000 p.p.m. of As_2O_3, is measured out with a burette and further diluted to the appropriate strength. This concentration of 5,000 p.p.m. is particularly convenient in making up cultures in 500-gram lots of soil, since the number of cubic centimeters added, multiplied by 10, gives the p.p.m. based on the weight of the air-dry soil.

The concentration series used in the tests on the 80 soils ran as follows: 0, 15, 40, 80, 140, 220, 340, 490, 680, and 920 p.p.m. As_2O_3 in the air-dry soil. All series were run in triplicate. In determining the amount of water required to moisten these soils, a simple method has been used. When 50-gram lots of the soils have been weighed into test tubes, water is added—2.5 cc, 5.0 cc, 7.5 cc, or 10.0 cc, according to the textural grade of the soil. After 24 hours, the depth of the soil column moistened is measured, and the volume of water necessary to wet 100 grams of soil calculated. By an appropriate factor, the volume needed in the cultures is determined. This method has proved simpler and more satisfactory than determining the moisture equivalent, since it allows for the moisture present in the air-dry soil and for factors of soil preparation that must be considered in the latter method.

Data on the water-holding capacities of the soils and on the weights of soil used in the cultures are reported in table 1.

EXPERIMENTAL RESULTS

Retests on Four Soil Types.—In order to remedy some of the difficulties experienced in the initial trial, a more extended experiment was set up, with an expanding series of concentrations ending with cultures containing 3,000 p.p.m.

The soils for this retest were more carefully selected than those in the earlier experiment. The Stockton adobe clay was carefully selected from an area along a fence, undisturbed for many years and never affected except by shallow plowing. The Columbia fine sandy loam of this and

later experiments was somewhat more fertile and a bit finer-textured than that of the previous tests. The Yolo clay loam and the Fresno sandy loam were the same.

TABLE 2

TOXICITY OF SODIUM ARSENITE IN 4 CALIFORNIA SOILS AS SHOWN BY GROWTH OF INDICATOR PLANTS; EFFECTS OF TIME AND CROPPING*

Sodium arsenite expressed as p.p.m. As_2O_3 in air-dry soil	Yolo clay loam		Stockton adobe clay		Fresno sandy loam		Columbia fine sandy loam	
	Height	Fresh weight	Height	Fresh weight	Height	Fresh weight	Height	Fresh weight
First run, harvested December 29, 1933								
p.p.m.	*cm*	*gm*	*cm*	*gm*	*cm*	*gm*	*cm*	*gm*
10	36	8.5	18	1.9	29	5.1	32	6.8
30	35	8.0	16	1.7	26	3.6	32	6.7
60	35	7.8	14	1.2	20	1.9	31	5.9
100	35	7.5	12	1.0	8	0.7	30	5.5
150	33	6.6	10	0.9	7	0.5	27	4.8
210	33	6.2	9	0.8	5	0.1	20	2.6
280	31	4.9	10	0.8	0	0.0	9	0.7
360	26	3.3	8	0.6	0	0.0	7	0.5
450	16	2.0	7	0.5	0	0.0	3	0.3
550	8	0.8	5	0.4	0	0.0	0	0.0
660	8	0.6	4	0.3	0	0.0	0	0.0
780	6	0.4	5	0.3	0	0.0	0	0.0
910	4	0.2	4	0.2	0	0.0	0	0.0
1,050	3	0.1	4	0.1	0	0.0	0	0.0
Check	36	9.1	21	2.0	28	5.5	33	7.3
Third run, harvested May 31, 1934								
p.p.m.	*cm*	*gm*	*cm*	*gm*	*cm*	*gm*	*cm*	*gm*
10	34	9.6	21	3.4	26	4.4	29	5.4
30	34	9.8	21	3.2	26	4.3	28	6.1
60	34	9.8	22	3.0	25	3.9	28	5.6
100	32	8.4	20	2.3	23	3.4	26	4.5
150	30	6.2	19	2.1	20	2.7	21	2.7
210	28	5.3	15	1.4	16	1.8	18	2.0
280	24	3.5	11	1.0	13	1.5	14	1.5
360	21	2.5	9	0.5	14	1.3	12	1.2
450	18	2.1	8	0.4	9	0.8	11	0.9
550	16	1.8	8	0.3	7	0.5	10	0.6
660	13	1.3	8	0.4	6	0.2	9	0.5
780	11	0.9	8	0.4	6	0.3	8	0.3
910	11	0.9	8	0.4	5	0.1	6	0.2
1,050	11	0.6	6	0.4	0	0.0	6	0.1
1,200	10	0.5	7	0.2	0	0.0	0	0.0
1,360	9	0.5	7	0.1	0	0.0	0	0.0
1,530	8	0.2	0	0.0	0	0.0	0	0.0
1,710	7	0.1	0	0.0	0	0.0	0	0.0
Check	30	8.1	20	3.1	23	4.3	26	5.1

* Each value given is an average of 5 replicates.

TABLE 2—(*Concluded*)

Sodium arsenite expressed as p.p.m. As_2O_3 in air-dry soil	Yolo clay loam		Stockton adobe clay		Fresno sandy loam		Columbia fine sandy loam	
	Height	Fresh weight	Height	Fresh weight	Height	Fresh weight	Height	Fresh weight
Fifth run, harvested January 9, 1935								
p.p.m.	*cm*	*gm*	*cm*	*gm*	*cm*	*gm*	*cm*	*gm*
10	29	5.9	21	2.4	25	3.7	28	4.8
30	30	6.3	22	2.8	26	3.5	27	4.8
60	29	6.0	22	2.6	25	3.5	28	5.3
100	29	6.5	23	3.4	26	3.5	29	5.4
150	31	6.9	25	3.7	26	3.4	29	5.4
210	31	6.4	23	3.0	23	2.8	27	4.6
280	30	6.1	22	2.8	23	2.6	25	3.4
360	*27*	*4.9*	*17*	*1.9*	*19*	*1.9*	*23*	*2.7*
450	26	4.5	18	1.7	15	1.4	20	1.9
550	24	3.7	12	1.2	11	0.8	18	1.5
660	23	3.1	13	1.3	11	0.7	17	1.4
780	22	2.7	12	1.2	10	0.6	14	1.1
910	21	2.4	11	1.2	9	0.5	13	0.9
1,050	19	2.0	11	1.1	9	0.5	11	0.7
1,200	17	1.5	11	1.0	8	0.3	11	0.6
1,350	15	1.2	11	0.8	8	0.3	10	0.5
1,530	13	1.0	10	0.7	7	0.2	9	0.4
1,710	12	0.9	10	0.5	6	0.1	8	0.4
1,900	12	0.9	9	0.5	6	0.1	8	0.3
2,100	11	0.7	8	0.5	5	0.1	7	0.3
2,310	10	0.7	8	0.4	0	0.0	7	0.3
2,530	9	0.5	7	0.3	0	0.0	7	0.3
2,760	9	0.5	7	0.3	0	0.0	6	0.3
3,000	9	0.5	6	0.3	0	0.0	6	0.3
Check	*26*	*5.0*	*20*	*3.0*	*25*	*3.5*	*26*	*4.5*
Seventh run, harvested November 14, 1935								
p.p.m.	*cm*	*gm*	*cm*	*gm*	*cm*	*gm*	*cm*	*gm*
150	..	...	..	...	16	1.9	..	...
210	..	...	..	...	15	1.9	18	2.7
280	..	...	14	1.8	14	1.6	16	1.8
360	24	5.4	14	1.6	12	1.5	14	1.5
450	24	4.8	12	1.2	11	1.1	13	1.3
550	23	3.9	10	1.0	9	0.7	12	1.0
660	21	3.1	10	1.0	8	0.6	10	0.9
780	20	2.7	10	1.1	8	0.5	9	0.7
910	18	2.3	11	1.1	7	0.4	9	0.6
1,050	15	1.7	11	1.2	7	0.4	7	0.4
1,200	14	1.5	11	1.1	6	0.3	5	0.2
1,360	13	1.4	10	1.0	6	0.3	4	0.1
1,530	*12*	*1.1*	*8*	*0.8*	*5*	*0.2*	*4*	*0.1*
1,710	10	1.1	7	0.6	5	0.2	4	0.1
1,900	10	0.8	7	0.4	4	0.2	3	0.1
2,100	8	0.6	6	0.4	3	0.1	3	0.1
2,310	*7*	*0.5*	*5*	*0.2*	*0*	*0.0*	*0*	*0.0*
2,530	7	0.4	5	0.2	0	0.0	0	0.0
2,760	6	0.5	4	0.2	0	0.0	0	0.0
3,000	6	0.4	3	0.1	0	0.0	0	0.0
Check	21	4.2	15	2.2	16	2.3	18	3.0

When complete, this experiment contained 24 concentrations and 4 checks, each consisting of 5 replicates. Similar series were established at about the same time for sodium chlorate and borax. The first 3 crops on the chlorate series were reported earlier (*6*), as were the first, third, and fifth crops of the borax tests (*9*). The first, third, fifth, and seventh crops of the present experiment on the arsenic series are given in table 2. In each run only the cultures having growth in one or more of the soils are reported, all higher concentrations having no growth. By the fifth run all concentrations in the Yolo and Stockton soils had so greatly decreased in toxicity that plants survived in them. Since the lower concentrations were producing crops as heavy as the checks or heavier, the first 4 were not included in the seventh run in table 2; and even higher concentrations were omitted in 3 of the soils.

The most noticeable result of the retest is the difference in behavior of the Stockton soil. Though producing a low yield, the plants survived through the lowest 13 concentrations; a fact indicating a toxicity similar to that of the Yolo clay loam. The change in toxicity, furthermore, practically kept pace with that of the Yolo soil. Evidently the results reported earlier (*6*) gave an inaccurate picture of the toxicity in adobe soils.

Tests on Eighty Soils.—Yield data on the eighty soils tested are presented in table 3. Obviously the toxicity results follow a definite pattern, toxicity being highest in the sands and lowest in the clays. There are a few notable exceptions, later to be considered in detail. The general relation may be more easily scrutinized in the summary in table 4, where averages for the 5 soil groups are compiled.

The water-holding capacities of the various soil groups, as shown in these averaged results, may be correlated with textural grade; and the arsenic toxicities show a related change. Conceivably, certain factors that enable the soil to hold water against the force of gravity are involved in the availability of applied arsenic to plants.

For comparing soil groups, a series of toxicity values have been calculated, based upon the yield of the untreated checks; these results, presented in table 4, are graphed in figure 1. Although the numbers in these averages are not great enough to give perfectly smooth curves and although the exceptional results on a few individual soils tend in places to overshadow the general relations, the correlation of toxicity and textural grade is obvious. The expression of this relation, regardless of the crops produced, is the principal finding in this study.

The relation of toxicity to textural grade is further illustrated by the crops in Oakley sand, Farwell loam, and Aiken clay loam shown in figure 2. These series all contain a 5 p.p.m. culture; and all concentrations being

TABLE 3

TOXICITY OF SODIUM ARSENITE IN 80 CALIFORNIA SOILS AS SHOWN BY GROWTH OF INDICATOR PLANTS

No.	Soil type	Date of harvest	Arsenic concentration—As_2O_3 in p.p.m. basis air-dry soil									
			0	15	40	80	140	220	340	490	680	920
			Fresh weight of plants									
	Sands											
			gm	*gm*	*gm*	*gm*	*gm*	*gm*	*gm*	*gm*	*gm*	*gm*
1	Holland loamy gravelly sand	Dec. 23, 1934	1.8	2.0	1.5	1.3	0.6	0.3	*			
2	Niland gravelly sand	June 5, 1935	1.0	0.7	0.4			*				
3	Oakley sand	Jan. 10, 1936	1.9	1.6	1.3	0.8	0.4	*				
4	Rositas fine sand	June 5, 1935	1.2	1.1	0.9	0.1		*				
5	Superstition gravelly sand	June 5, 1935	1.6	1.3	1.4	0.9	0.1	*				
6	Tujunga sand	June 4, 1935	0.5	0.4	0.6	0.1	*					
	Gravelly and sandy loams											
			gm	*gm*	*gm*	*gm*	*gm*	*gm*	*gm*	*gm*	*gm*	*gm*
7	Aiken gravelly loam	Dec. 23, 1934	1.6	1.7	1.6	1.8	1.7	1.8	1.6	0.4	0.3	0.1
8	Arbuckle gravelly sandy loam	Dec. 23, 1934	2.1	2.3	1.8	1.9	0.9	0.3	*			
9	Chualar fine sandy loam	Jan. 10, 1936	5.3	4.9	2.8	1.9	0.1		*			
10	Columbia fine sandy loam	June 4, 1935	4.4	4.8	4.0	3.0	1.5	0.3	*			
11	Corning gravelly loam	Dec. 23, 1934	1.6	1.5	1.4	1.2	0.8	0.3	0.2	*		
12	Delano fine sandy loam	Jan. 10, 1936	4.5	4.5	3.9	2.6	0.9	0.7	0.1			
13	Foster fine sandy loam	Jan. 10, 1936	3.3	2.8	0.4	0.1		*				
14	Fresno sandy loam	June 4, 1935	3.0	2.2	1.4	0.1	*					
15	Greenfield coarse sandy loam	Jan. 10, 1936	4.3	3.8	1.2	0.3	0.1	*				
16	Hanford sandy loam	Jan. 10, 1936	4.3	4.0	2.5	0.7	0.2	0.1	*			
17	Hanford fine sandy loam	Jan. 10, 1936	4.0	3.4	2.9	1.0	0.2	*				
18	Meloland fine sandy loam	June 5, 1935	1.9	1.9	1.5	1.0	0.2	*				
19	Merced fine sandy loam	Jan. 10, 1936	4.4	3.8	3.1	1.7	0.4	*				
20	Oakdale coarse sandy loam	Jan. 10, 1936	3.0	2.8	2.4	0.6	0.1		*			
21	Ramona sandy loam	June 5, 1935	3.0	3.0	2.6	1.6	0.3			*		
22	Redding gravelly loam	Jan. 10, 1936	3.3	3.1	2.8	2.5	2.1	0.7	0.1	*		
23	Rocklin sandy loam	Dec. 23, 1934	1.5	1.3	1.2	0.8	0.5	0.2	0.1		*	
24	Salinas fine sandy loam	Jan. 10, 1936	3.7	3.5	3.0	1.9	1.3	0.5	*			
25	Sierra gravelly loam	Dec. 23, 1934	1.8	1.9	1.6	1.8	1.6	1.5	0.7	0.6	0.2	*
26	Sierra sandy loam	Dec. 23, 1934	3.2	3.1	2.7	2.4	1.2	0.3	0.1	*		
27	Sites fine sandy loam	Dec. 23, 1934	1.9	1.9	1.4	1.3	0.7	0.2	0.1	*		
28	Tulare fine sandy loam	Jan. 10, 1936	2.1	1.8	1.3	0.3	0.2		*			
29	Yolo fine sandy loam	Dec. 22, 1934	3.5	3.3	3.1	2.9	2.6	0.6	0.3	0.2	*	
	Loams											
			gm	*gm*	*gm*	*gm*	*gm*	*gm*	*gm*	*gm*	*gm*	*gm*
30	Egbert loam	June 4, 1935	3.9	3.4	3.2	2.7	2.2	1.6	1.0	0.2	*	
31	Farwell loam	Jan. 10, 1936	7.3	7.2	6.1	5.4	3.2	1.0	0.1	*		
32	Gridley loam	Jan. 10, 1936	2.5	2.7	2.6	2.5	2.5	0.5	0.2			*
33	Honcut loam	Jan. 10, 1936	4.1	3.8	3.4	2.5	1.3	0.3	0.1	*		
34	Madera loam	June 5, 1935	3.2	2.7	2.6	2.2	1.7	0.5	0.3		*	
35	Panoche light loam	Jan. 10, 1936	2.7	2.4	2.2	0.8	0.2	0.2		*		
36	Pinole loam	Jan. 10, 1936	1.4	1.4	1.4	1.2	0.9	0.7	0.5		*	

* Seeds in cultures at this and higher concentrations failed to germinate. Fresh weight of plants in cultures between reported weight and point of no germination was less than 0.1 gram.

TABLE 3—(*Concluded*)

No.	Soil type	Date of harvest	Arsenic concentration—As_2O_3 in p.p.m. basis air-dry soil									
			0	15	40	80	140	230	340	490	680	920
			Fresh weight of plants									
	Loams—(*Continued*)											
			gm	*gm*	*gm*	*gm*	*gm*	*gm*	*gm*	*gm*	*gm*	*gm*
37	Placentia light loam	June 4, 1935	2.7	2.4	2.2	1.7	0.1		*			
38	Pleasanton loam	Jan. 10, 1936	4.4	4.2	4.0	2.4	0.6	0.2	*			
39	Pond heavy loam	Jan. 10, 1936	0.0		*							
40	San Joaquin loam	June 5, 1935	3.4	2.6	2.7	1.8	1.3	0.6	0.2		*	
41	Tehama loam	Jan. 10, 1936	2.6	2.4	2.2	0.8	0.2		*			
42	Vina loam	Jan. 10, 1936	3.3	3.6	3.4	3.2	3.0	0.9	0.3		*	
43	Yolo loam	Dec. 22, 1934	3.8	3.6	3.5	3.1	2.2	0.3	0.2	0.1	*	
	Silt and clay loams											
			gm	*gm*	*gm*	*gm*	*gm*	*gm*	*gm*	*gm*	*gm*	*gm*
44	Aiken clay loam	Jan. 10, 1936	1.0	1.0	0.9	0.9	0.9	0.8	0.7	0.6	0.6	0.3
45	Antioch clay loam	Jan. 10, 1936	3.9	4.5	3.9	4.0	2.8	1.2	0.5	*		
46	Arbuckle clay loam	Dec. 23, 1934	2.4	2.4	1.9	1.9	1.1	1.3	0.3	0.1	*	
47	Chino silty clay loam	June 5, 1935	1.6	1.5	1.5	1.4	0.7	0.1		*		
48	Columbia silty clay loam	June 5, 1935	4.2	3.8	3.7	2.8	2.7	2.4	2.4	1.5	1.1	0.8
49	Mariposa silt loam	Dec. 22, 1934	2.0	1.9	1.8	1.4	1.5	0.7	0.6	0.3	*	
50	Marvin silty clay loam	Jan. 10, 1936	3.4	3.9	3.5	3.1	1.9	0.7	0.4		*	
51	Ramada silt loam	Jan. 10, 1936	6.5	6.3	6.2	3.8	1.6	0.3	0.1	*		
52	Sacramento clay loam	June 5, 1935	4.1	4.2	3.9	2.7	2.0	0.8	0.5			*
53	Yolo silt loam	Dec. 22, 1934	8.9	8.6	6.9	6.5	3.4	0.9	0.3	0.2	*	
54a	Yolo clay loam	Dec. 22, 1934	9.8	9.4	9.5	8.8	5.1	1.4	0.4	0.2	*	
54b	Yolo clay loam	June 4, 1935	8.7	8.8	7.6	6.9	5.8	4.0	0.6	0.4	*	
	Clays											
			gm	*gm*	*gm*	*gm*	*gm*	*gm*	*gm*	*gm*	*gm*	*gm*
55	Alamo adobe clay	Jan. 10, 1936	1.7	1.7	1.6	1.4	1.3	0.7	0.5	0.3	0.2	0.1
56	Anita adobe clay	Jan. 10, 1936	2.1	2.1	1.8	1.7	1.2	1.1	0.9	0.7	0.2	0.1
57	Capay adobe clay	Dec. 23, 1934	3.7	3.7	3.4	3.5	3.1	2.1	1.4	1.5	0.5	0.5
58	Clear Lake adobe clay	June 4, 1935	1.6	1.5	1.4	1.1	1.1	0.7	0.4	0.2	0.1	
59	Conejo adobe clay	Jan. 10, 1936	1.8	1.9	1.5	1.2	0.8	0.8	0.7	0.5	0.3	0.2
60	Diablo adobe clay	Jan. 10, 1936	2.6	2.4	1.9	1.5	0.8	0.4	0.2	0.2	0.1	
61	Dublin adobe clay	Jan. 10, 1936	4.7	4.9	4.6	4.4	4.3	3.7	3.2	2.0	0.5	0.3
62	Dunnigan clay	Dec. 23, 1934	1.8	1.8	1.6	1.1	0.3	0.3	0.2	0.2	*	
63	Esparto clay	Dec. 22, 1934	4.4	4.5	4.0	3.9	3.2	2.5	1.4	0.5	0.1	
64	Farwell adobe clay	Jan. 10, 1936	2.5	2.4	2.4	1.9	1.6	1.2	0.8	0.7	0.3	0.1
65	Fresno light clay	Jan. 10, 1936	1.0	1.5	1.3	0.6	0.4	0.3	0.2	0.2		
66	Imperial clay	June 5, 1935	3.0	2.9	2.8	2.4	2.1	1.6	0.8	0.5		
67	Landlow adobe clay	Jan. 10, 1936	1.8	2.2	2.1	2.0	1.7	1.6	0.8	0.6	0.2	
68	Madera clay	Jan. 10, 1936	2.3	2.1	1.7	1.6	1.1	0.9	0.5	0.5	0.1	
69	Merced adobe clay	Jan. 10, 1936	1.5	1.5	1.5	1.3	1.1	1.1	0.7	0.4	0.3	0.2
70	Montezuma adobe clay	June 4, 1935	2.3	2.1	1.8	1.2	1.1	0.9	0.5	0.3	0.2	
71	Montezuma adobe clay	Jan. 10, 1936	2.1	2.3	2.0	2.1	1.9	1.0	0.5	0.1	*	
72	Panoche adobe clay	Jan. 10, 1936	8.1	8.1	6.9	6.6	5.4	3.7	2.5	0.7	0.4	0.2
73	Porterville adobe clay	Jan. 10, 1936	4.2	3.8	3.5	2.0	0.9	0.3	0.2	0.2	*	
74	Salinas clay	Jan. 10, 1936	3.5	3.5	3.3	3.2	1.1	0.3	0.2		*	
75	Sites adobe clay	Dec. 22, 1934	2.8	3.0	2.5	2.0	1.6	1.1	0.5	0.3	0.1	0.1
76	Stockton adobe clay	April 24, 1936	2.9	2.3	1.8	1.6	1.5	0.8	0.6	0.4	0.1	
77	Tulare clay	Jan. 10, 1936	1.6	1.5	1.4	0.5	0.3	0.1	*			
78	Willows adobe clay	Dec. 23, 1934	2.0	2.2	1.9	1.6	1.2	0.7	0.7	0.4	0.1	0.1
79	Yolo adobe clay	Jan. 10, 1936	1.9	1.9	1.7	1.5	0.7	0.2	0.1		*	
80	Yolo clay	Dec. 22, 1934	4.4	4.8	4.4	4.5	4.1	3.9	2.6	2.2	1.0	0.1

* Seeds in cultures at this and higher concentrations failed to germinate. Fresh weight of plants in

comparable in the 3 series, the heavier soils show obviously lower toxicities, while crop-producing power (table 3) varies in no regular way with textural grade.

Figure 3, showing 3 toxicity series in adobe soils, further illustrates this point. Although the crop yields vary widely, being high in the Panoche soil, intermediate in Dublin, and low in Merced (table 3), toxicities are strictly comparable in the 3 soils. These series lack the 5-p.p.m. cultures but have the 920-p.p.m. ones.

TABLE 4

SUMMARY OF RESULTS: TOXICITY OF SODIUM ARSENITE IN CALIFORNIA SOILS AS SHOWN BY GROWTH OF INDICATOR PLANTS

Soils	Water	Arsenic concentration—As_2O_3 in p.p.m. on the basis of air-dry soil									
		0	15	40	80	140	220	340	490	680	920
						Fresh weight of plants					
	per cent	*gm*	*gm*	*gm*	*gm*	*gm*	*gm*	*gm*	*gm*	*gm*	*gm*
Sands	11.4	1.33	1.18	1.02	0.53	0.18	0.05				
Gravelly and sandy loams	14.3	3.12	2.88	2.20	1.46	0.77	0.33	0.14	0.05		
Loams	17.9	3.49	3.26	3.04	2.33	1.48	0.52	0.21	0.02		
Silt and clay loams	22.7	4.71	4.69	4.28	3.68	2.46	1.22	0.57	0.28	0.14	0.05
Clays	27.6	2.82	2.79	2.50	2.18	1.70	1.23	0.81	0.52	0.18	0.08
						Results expressed as a percentage of checks					
	per cent	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*
Sands	11.4	100	88.8	76.7	30.6	13.5	3.8				
Gravelly and sandy loams	14.3	100	91.6	70.5	46.8	24.6	10.6	4.5	1.6		
Loams	17.9	100	93.5	87.1	66.8	42.4	14.9	6.0	0.6		
Silt and clay loams	22.7	100	99.5	91.0	78.1	52.3	25.9	12.1	5.9	3.0	1.1
Clays	27.6	100	99.2	88.6	77.4	60.3	43.6	28.7	18.4	6.4	2.8

A more detailed study of the data in table 3 shows many minor variations in toxicity within the groups designated on the basis of soil texture. Though the general relation shown between texture and toxicity is valuable, its usefulness would be enhanced if the exceptions could be explained and anticipated in the field, as is possible in several cases.

The soils most obviously out of agreement are Aiken gravelly loam, Aiken clay loam, and Columbia silty clay loam. The two Aiken soils—residual soils from basic igneous rock—are deep red. They have demonstrated an immense capacity to render phosphate unavailable and by analogy should do the same with arsenic. Tests in the field and greenhouse show this to be true. Earlier, the red iron oxide content of these soils was thought to explain their immense capacity to reduce arsenic tox-

icity (*10*). Judging from recent experiments, however, peculiar colloids at least partly account for this phenomenon. This property of rendering arsenic unavailable, though common to all red soils, is less pronounced in those from acid igneous rocks. Among the gravelly and sandy loams (in addition to the Aiken), the Corning, Delano, Redding, Rocklin, Sierra, and Sites soils all contain more or less of this material and all show relatively low toxicities. Incidentally, red iron oxide has been used to lower

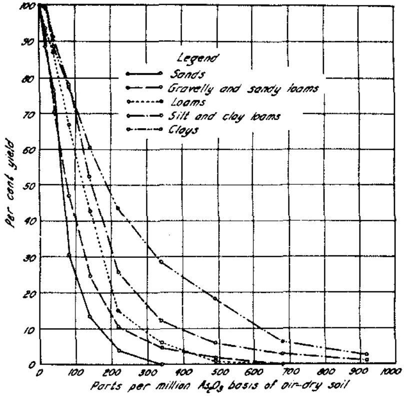

Fig. 1.—The relation between textural grade and arsenic toxicity from the summarized results of table 4.

arsenic solubility in filter beds made of soil (*10*). A great capacity for reducing arsenic toxicity is apparently characteristic of all red soils used in these tests, so that dosages must be set with this factor in mind, more arsenic being required than would ordinarily be applied on the basis of textural grade alone.

The Columbia soils, recent alluvial deposits from the floodwaters of the Sacramento River, come from a mixture of acid and basic igneous rocks from the Sierras with sedimentary rocks from the Coast Range. During deposition, the heavier particles settle out along the river banks, while the finer ones are deposited farther from the main channel. To obtain a silty clay loam it was necessary to visit the very edge of the alluvial deposits. The source of soil used in these experiments was a spot

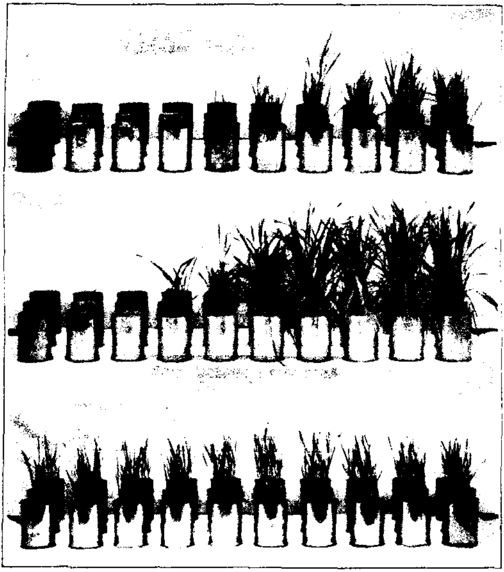

Fig. 2.—Culture series in Oakley sand, Farwell loam, and Aiken clay loam illustrating the relation between textural grade and arsenic toxicity. The As_2O_3 concentrations are 680, 490, 340, 220, 140, 80, 40, 15, 5, and 0 p.p.m., based on the air-dry soil.

about 3 miles west of Sacramento near the main highway, where the Columbia soil occurs as a thin layer about 18 inches deep, overlying an extremely heavy, black Sacramento clay. Such a soil might be expected to contain a large proportion of the colloidal fractions characteristic of the soils from the three available rock sources. Though the sample used contained considerable silt, it undoubtedly had, in addition, enough colloids from the red Aiken and Sierra soils and the brown Yolo soils to explain the low toxicity. The coarser Columbia fine sandy loam obtained only a few miles farther north consisted largely of fine sand and silt, without enough of these active colloids to give it an unusual behavior.

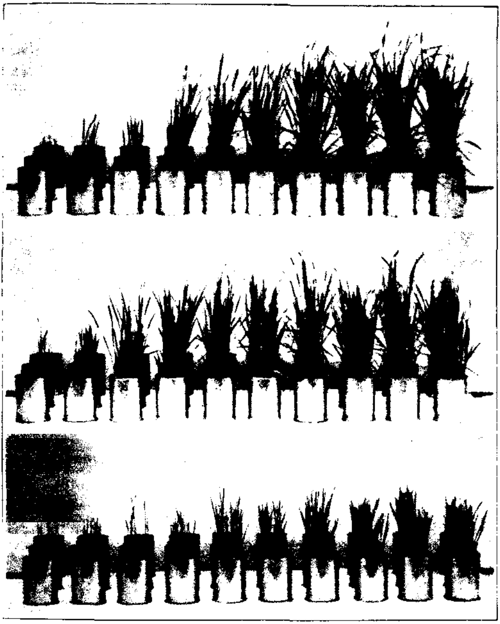

Fig. 3.—Culture series showing arsenic toxicity in Panoche adobe clay, Dublin adobe clay, and Merced adobe clay. Although fresh-weight yields of crops on these soils vary widely, the toxicity is approximately the same in all three. These series lack the 5 p.p.m. cultures. The As_2O_3 concentrations are 920, 680, 490, 340, 220, 140, 80, 40, 15, and 0 p.p.m.

Exceptional results are also shown by the Yolo soil in these experiments. Being easily obtainable, a full series of textural grades of this soil was used to show the effect of particle size within a single soil series. The choice of the Yolo series for this purpose was unfortunate in that the two lighter types act like heavy soils, whereas the adobe behaved like a lighter type. The behavior of the lighter types may be explained by their colloids, which have an extreme capacity to render arsenic unavailable.

This observation has been made for phosphates but has no important bearing on crop production, since phosphorus is apparently not deficient in Yolo soils. In soil sterilization with arsenic, however, this capacity is a critical factor, for Yolo soils in the field require heavy arsenic applications (*5*), and toxicity decreases rapidly after the initial treatment (*5*, *6*, and table 2).

The abnormal behavior of the Yolo adobe clay is less readily explained. This soil required no more water for moistening than the clay and less than the clay loam. Though its colloids are of such a form as to give this soil adobe characteristics, the total colloid content may be less than that of the other two grades. As is shown in another paper in this issue (*13*, table 3), the capacity of this soil to render arsenic insoluble after several weeks is less than that of the clay.

DISCUSSION

To be widely applicable, the general relations brought out by these studies should rest upon chemical interpretation and practical confirmation through field-plot testing. Chemical studies on a number of these soils appear in an accompanying paper (*13*); a few field-plot tests will be mentioned here, but plot results will be presented more completely in a later paper.

The general problem of toxicity measurement has been discussed in detail by Cook (*2*, *3*, *4*). The present method of measuring and reporting height and fresh weight of the indicator plants 30 days after planting in soils moistened with the herbicide solutions was standardized several years ago and has proved entirely satisfactory. These values, however, *are only comparative; for practical use they must be calibrated by checking against graded series of treated plots*. Although this checking has not been extensively done, growing of the indicator plants on soils from plots having known degrees of sterility has shown that yields of 0.2 gram or less per can represent practical sterilization. Such comparisons seem sufficiently reliable to justify a tentative schedule of dosages, offered later in this paper.

Since fresh weight is by far the more valuable of the two toxicity criteria used, height has been omitted from tables 3, 4, and 5. Obviously, relative growth rate (*4*) cannot be used as a criterion of toxicity in the type of testing reported here, since the soil cultures could not be returned to the original weight for determination of growth increments. The work involved in repeated weighings on the large numbers of cultures run simultaneously in these tests was, furthermore, not feasible.

Before making the more practical interpretations, the errors and limitations of the biological testing methods used should be considered. Since the greenhouse in which these tests were conducted had only partial temperature control and practically no control of light, humidity, and length of day, results from culture series run at different seasons vary. Table 5 reports tests conducted at different dates upon the same soils. These data illustrate variations in toxicity resulting from the lack of constant culture conditions and, in the cases of Yolo clay loam and Stockton adobe clay, from the use of different samples. They emphasize the desirability of conducting comparative tests simultaneously on as many samples as possible. The soils in table 3 were tested in 3 lots, 2 of 20 each and 1 of 40. Though testing all 80 at one time would have been better, the work presents practical difficulties. Had it been done, the general relation shown between texture and toxicity would probably not have been appreciably changed.

The moisture conditions of the cultures are another matter for consideration. One might think that allowing the cultures to dry down periodically to the permanent wilting point would increase the arsenic concentration and hence the toxicity. In certain series, the moisture was varied in a number of soils (footnotes ¶ and ||, table 5). Judging from the results, arsenic toxicity is not seriously affected by the method of watering. This matter will be discussed more fully in a companion paper (*13*).

The biological test is definitely limited in scope by the sensitivity of the indicator plant. Since, however, the practical application of the results is in weed control, this drawback is not serious. The biological method, furthermore, gives a direct index to the availability and hence to the toxicity or crop-limiting power of the toxicant, which is impossible to obtain by chemical analysis. Considering the easy operation and the simple, inexpensive equipment needed, this method is very practical for testing toxicity of herbicides in soils.

RECOMMENDED DOSAGES OF ARSENIC FOR SOIL STERILIZATION

Clearly, these studies show that arsenic dosages for soil sterilization will vary between wide limits. Recommendations can at best be only approximate because of the complex relations between toxicity as related to availability, permanence as affected by leaching, and susceptibility as determined by the arsenic tolerance of the weed species concerned. Table 6 presents a dosage schedule based on plots and the present toxicity

TABLE 5

COMPARATIVE RESULTS OF TOXICITY TESTS ON REPEATED RUNS WITH SODIUM ARSENITE IN CALIFORNIA SOILS

Soil type	Run No.	Date of harvest	Arsenic concentration—As_2O_3 in p.p.m. on the basis of air-dry soil									
			0	15	40	80	140	220	340	490	680	920
			Fresh weight of plants									
			gm	*gm*	*gm*	*gm*	*gm*	*gm*	*gm*	*gm*	*gm*	*gm*
Columbia fine sandy loam	1*	June 10, 1933*	4.6	4.6	4.4	4.1	3.0	1.7	0.3	0.1		
	2†	Dec. 29, 1933†	7.3	6.8	6.5	5.7	5.0	2.2	0.5	0.1		
	3‡	June 4, 1935‡	4.4	4.8	4.0	3.0	1.5	0.3				
	4§	Apr. 24, 1936§	13.5	11.1	9.9	5.5	1.4	0.2				
Delano fine sandy loam	1‡	Jan. 10, 1936‡	4.5	4.5	3.9	2.6	0.9	0.7	0.1			
	2¶	Mar. 16, 1937¶	2.9	2.5	1.8	0.7	0.3	0.5				
	3‖	Mar. 16, 1937‖	2.6	2.2	1.7	0.6	0.3	0.2				
Fresno sandy loam	1*	June 10, 1933*	2.9	2.4	1.4	0.6	0.4	0.2				
	2†	Dec. 29, 1933†	5.5	4.6	3.1	1.2	0.5	0.1				
	3‡	June 4, 1935‡	3.0	2.2	1.4	0.1						
	4§	Apr. 24, 1936§	7.2	4.0	2.6	0.5	0.2					
	5¶	Mar. 16, 1937¶	4.7	3.8	2.2	0.7	0.2	0.2				
	6‖	Mar. 16, 1937‖	4.4	4.3	2.3	0.6	0.2					
Greenfield coarse sandy loam	1‡	Jan. 10, 1936‡	4.3	3.8	1.2	0.3	0.1					
	2¶	Mar. 16, 1937¶	3.2	2.7	1.1	0.7	0.3					
	3‖	Mar. 16, 1937‖	1.4	1.7	0.9	0.6	0.2					
Sierra sandy loam	1‡	Dec. 23, 1934‡	3.2	3.1	2.7	2.4	1.2	0.3	0.1			
	2¶	Mar. 16, 1937¶	3.0	2.5	2.3	1.6	0.7					
	3‖	Mar. 16, 1937‖	2.3	2.2	2.0	0.3	0.1					
Yolo fine sandy loam	1‡	Dec. 22, 1934‡	3.5	3.3	3.1	2.9	2.6	0.6	0.3	0.2		
	2§	Apr. 24, 1936§	5.4	5.5	4.7	4.4	2.4	0.4				
Egbert loam	1‡	June 4, 1935‡	3.9	3.4	3.2	2.7	2.2	1.6	1.0	0.2		
	2¶	Mar. 16, 1937¶	8.2	8.6	8.4	8.5	6.7	3.7	2.3	1.1	1.1	0.4
	3‖	Mar. 16, 1937‖	5.8	5.2	5.6	5.3	4.1	3.8	1.6	0.6	0.7	0.1
Aiken clay loam	1‡	Jan. 10, 1936‡	1.0	1.0	0.9	0.9	0.9	0.8	0.7	0.6	0.6	0.3
	2§	Apr. 24, 1936§	3.2	3.5	3.4	2.9	2.4	2.2	2.1	1.8	1.1	0.7
Arbuckle clay loam	1‡	Dec. 23, 1934‡	2.4	2.4	1.9	1.9	1.1	1.3	0.3	0.1		
	2§	Apr. 24, 1936§	4.5	4.2	3.6	3.3	3.0	2.9	1.5	0.4		
Sacramento clay loam	1‡	June 5, 1935‡	4.1	4.2	3.9	2.7	2.0	0.8	0.5			
	2¶	Mar. 16, 1937¶	5.2	5.3	5.4	4.9	4.0	3.7	2.6	1.9	0.8	0.1
	3‖	Mar. 16, 1937‖	2.1	3.5	3.6	3.1	2.6	2.8	2.1	0.7	0.1	

* By interpolation from Crafts (*6*).
† By interpolation from table 2.
‡ From table 3.
§ From Crafts (*7*).
¶ From Rosenfels and Crafts (*13*); watered daily.
‖ From Rosenfels and Crafts (*13*); watered as needed.

TABLE 5—(*Concluded*)

Soil type	Run No.	Date of harvest	Arsenic concentration—As_2O_3 in p.p.m. on the basis of air-dry soil									
			0	15	40	80	140	220	340	490	680	930
			Fresh weight of plants									
			gm	*gm*	*gm*	*gm*	*gm*	*gm*	*gm*	*gm*	*gm*	*gm*
Yolo clay loam	1*,[a]	June 10, 1933*,[a]	8.6	8.6	7.0	7.2	5.7	4.8	2.3	1.0	0.3	
	2†,[a]	Dec. 29, 1933†,[a]	9.1	8.4	7.9	7.6	6.7	5.8	3.7	1.5	0.5	0.2
	3‡,[b]	Dec. 22, 1934‡,[b]	9.8	9.4	9.5	8.8	5.1	1.4	0.4	0.2		
	4‡,[b]	June 4, 1935‡,[b]	8.7	8.8	7.6	6.9	5.8	4.0	0.6	0.4		
	5§,[c]	Apr. 24, 1936§,[c]	18.6	17.5	14.2	12.4	8.9	5.4	0.3			
Stockton adobe clay	1*,[a]	June 10, 1933*,[a]	2.9	2.3	2.0	1.6	0.5	0.2	0.1	0.1	0.1	
	2†,[b]	Dec. 29, 1933†,[b]	2.0	1.8	1.5	1.1	0.9	0.8	0.7	0.5	0.3	0.2
	3‡,[c]	Apr. 24, 1936‡,[c]	2.9	2.3	1.8	1.8	1.5	0.8	0.6	0.4	0.1	
Yolo clay	1‡	Dec. 22, 1934‡	4.4	4.8	4.4	4.5	4.1	3.9	2.6	2.2	1.0	0.1
	2¶	Mar. 16, 1937¶	4.1	3.8	3.6	3.1	2.8	2.5	0.9	1.0	0.1	
	3‖	Mar. 16, 1937‖	3.5	3.3	3.2	3.3	2.9	1.5	1.3	1.3	0.5	0.3
Yolo adobe clay	1‡	Jan. 10, 1936‡	1.9	1.9	1.7	1.5	0.7	0.2	0.1			
	2¶	Mar. 16, 1937¶	3.2	3.3	3.3	2.8	1.6	1.1	0.1	0.1		
	3‖	Mar. 16, 1937‖	2.8	2.8	2.7	2.8	2.0	1.7	0.1			

* By interpolation from Crafts (*6*).

† By interpolation from table 2.

‡ From table 3.

§ From Crafts (*7*).

¶ From Rosenfels and Crafts (*15*); watered daily.

‖ From Rosenfels and Crafts (*15*); watered as needed.

[a] Soil sample collection in 1932.

[b] Soil sample collection in 1933.

[c] Soil sample collection in 1935.

studies in the greenhouse. The groupings are somewhat arbitrary and require liberal interpretation to meet specific problems.

In the high-toxicity group are the coarse, gritty soils having little colloidal matter. Such soils not only are common on the alluvial fans and upper flood-plain areas of the large valleys of California but also occur as surface material in many foothill and mountain regions, on old valley fills, bench lands, wind-modified areas, and heavily leached areas. Lands of this type are developed by man by the deposition of gravel and rock in roadways, railroad roadbeds, parking areas, and various yards and lots used for stacking lumber and the raw materials for manufacture. Vast areas of such lands could be profitably sterilized with arsenic with little poisoning hazard to livestock and at a great saving of hand labor.

In the intermediate-toxicity range lie the loams, silt loams, and those clay loams that are developed directly from acid igneous rocks or highly weathered from other rocks; also lighter soils from basic igneous and sedimentary rocks. Many agricultural soils of California lie in this range,

and their successful sterilization requires appreciably heavier dosages than with the high-toxicity type.

The heavier soils of the clay and adobe clay types, together with the intermediate red soils from basic igneous rocks and brown soils from sedimentary rocks, demand heavy arsenic dosages; and their successful sterilization requires special technique in application.

In soil sterilization, two factors should be kept in mind: first, the immediate effect of the application; second, the persistence of the treatment. Application of a heavy dosage to sterilize the soil for a long time

TABLE 6

DOSAGE RECOMMENDATIONS FOR THE USE OF ARSENIC IN SOIL STERILIZATION ON CALIFORNIA SOILS

Soil			Toxicity group	Dosage,* As_2O_3† pounds per square rod
Texture	Type	Factors affecting arsenic availability		
Light and coarse	Sands and gravels, sandy and fine sandy loams	Normal	High	2–4
		Red or recent alluvial	Intermediate	4–8
Medium	Loams and silt loams	Normal	Intermediate	4–6
		Red or recent alluvial	Low	12
Heavy	Clay loams‡, clays, and adobe clays	Normal	Low	8–12
		Red or recent alluvial	Very low	12–20

* Values given in this table represent total dosages; this amount may be applied in several light treatments to meet the requirements of heavy soils or conditions of severe leaching.

† Since commercial sodium arsenite varies in As_2O_3 content, the weight of sodium arsenite required per square rod will depend upon the composition of the particular product being used.

‡ Clay loams from acid igneous rocks belong in the intermediate toxicity group and require a dosage of about 6 pounds per square rod.

would on first thought seem most economical. Where, however, leaching is severe (annual precipitation of 30 inches or more) or where the soil colloids cause low toxicity, losses of arsenic will be high, and the persistence of the treatment may not meet expectations. Under these latter conditions, a light annual application, though increasing the cost, minimizes losses from leaching and other causes. Evidently soils in the low-toxicity range require this type of treatment.

Leaching is an important factor in arsenic treatment of soils. Thus, Raynor found (*12*, p. 28–29) that the depth of penetration of sodium arsenite was influenced by the date of application since this was related to the rainfall. Under constant leaching, as in the banks of an unlined irrigation ditch, soil sterilization is not effective, all of the arsenic being removed by the seeping water. In regions of heavy rainfall, sterilization upon a given soil type is less permanent than in arid regions.

In connection with sterilization methods, arsenic trioxide (white arsenic) should be mentioned. This material, already used in plot studies (*5*), promises to become more popular when its special characteristics are better understood. Being relatively insoluble, it will lie in the soil for a year or more and gradually pass into solution, becoming tied up in high concentration in the top soil. According to experiments under central California conditions, one year is required to develop an effective toxicity in the soil. After the first year it is as effective as sodium arsenite, and because of its slow solution it lasts somewhat longer. This dry material, mixed with enough chlorate to give sterilization during the first year, should be the best reagent on heavy soils. Plot tests apparently bear out this conclusion (*5*).

In contrast to the retention of arsenic in the surface layer, common on heavy soils, a 12- to 20-inch penetration of sodium arsenite solution is common in light soils (*5*). This may be advantageous in controlling shallow-rooted perennials (*5, 12*). Consequently, the form of arsenic used should be related to the problem, and its varied behavior utilized to accomplish the ends in view.

The problems posed in the Introduction may be answered, at least in part, from the results of these studies. Concerning the type of arsenic compound to use in soil sterilization, the answer has already been indicated. For immediate results and for deep penetration on sandy soils from acid igneous rocks, sodium arsenite is preferable. In many other soils, especially heavy ones, red ones, and those from sedimentary rocks, decrease in toxicity is a serious factor; and to avoid excessive loss, either light annual application of sodium arsenite or the use of the less soluble trioxide seems advisable.

RECLAMATION OF ARSENIC-TREATED SOILS

From the soil-conservation standpoint, the slow accumulation of arsenic from compounds of low solubility to a toxic level in the soil is a serious problem (*11*). It means that a large reserve of insoluble arsenic is present, and that reduction in available arsenic must depend largely upon extensive leaching or upon the supplying of additional material capable of rendering arsenic unavailable. Though the use of iron oxides, or possibly red soils like Aiken clay loam, as soil amendments to reduce such toxicity offers an interesting field for research (*1*), nevertheless the slow solution of the residual, slightly soluble arsenic in the soil presents further difficulties. Apparently the continued use of arsenicals of low solubilty as insecticides on crops should be avoided, at least on light soils, for this method seems the best for providing lasting soil sterilization.

Where crop reduction follows the application of sodium arsenite, table 2 (p. 183) indicates that the toxicity may be greatly reduced over a period of time; and if the damage is not excessive, the soil may be reclaimed for agricultural use. But crop reduction following the continued use of slightly soluble arsenicals is a different matter; for the large reserve of arsenic present constitutes a supply capable of producing a long-continued toxicity. For reasons indicated above, even the use of soil amendments may not solve this problem. Where serious sterilization occurs, leaching would seem the only answer. Arsenic applications have not been effective below the water line in unlined irrigation ditches, and apparently the slow percolation of water will carry away almost any amount of arsenic in time.

SUMMARY

Biological tests show that arsenic toxicity is high in Fresno sandy loam, intermediate in Columbia fine sandy loam, and low in Yolo clay loam and Stockton adobe clay. Variation from previous tests may be explained by differences in the soil samples.

Repeated cropping shows that arsenic toxicity decreased in all 4 of these soils until, with the seventh crop, plants in the Yolo and Stockton soils survived in cultures containing 3,000 p.p.m. As_2O_3 in the air-dry soil. In the first crop test, no plants grew in cultures having more than 1,050 p.p.m. As_2O_3.

With repeated cropping, differences between Fresno and Columbia soils diminished. Though the limiting arsenic concentrations with the first crop were 280 and 550 p.p.m. As_2O_3, respectively, plants survived in cultures having 2,100 p.p.m. or more by the seventh cropping.

According to extensive tests involving short toxicity series in 80 California soils, arsenic toxicity can be correlated with texture, being high in sandy soils and low in clays. The most notable exceptions occur among the red soils, all of which, by rendering much arsenic unavailable, act like heavier types.

Arsenic sterilization on coarse, gritty soils in California requires a dosage of 2 pounds As_2O_3 per square rod.

Loams, silt loams, and those clay loams that are developed directly from acid igneous rocks or are highly weathered from other rocks require from 4 to 6 pounds per square rod.

Clays and adobe clays and some clay loams demand applications of from 8 to 12 pounds per square rod.

Red soils or recent alluvial soils from sedimentary rocks require approximately twice as much arsenic for a given type.

Light annual applications of soluble arsenic or use of dry arsenic trioxide with the addition of about 10 per cent sodium chlorate may be less wasteful on soils that render much arsenic unavailable.

Heavy leaching tends to reduce the concentration of available arsenic in the soil.

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ARSENIC FIXATION IN RELATION TO THE STERILIZATION OF SOILS WITH SODIUM ARSENITE

R. S. ROSENFELS AND A. S. CRAFTS

ARSENIC FIXATION IN RELATION TO THE STERILIZATION OF SOILS WITH SODIUM ARSENITE[1,2]

R. S. ROSENFELS[3] AND A. S. CRAFTS[4]

INTRODUCTION

DATA FROM GREENHOUSE EXPERIMENTS on the toxicity of arsenic to oats in 80 California soils are reported by Crafts and Rosenfels (*7*)[5] in another paper of this issue. In most of the soils tested, texture predominated as a determiner of toxicity; that is, toxicity was greatest in light and least in heavy soils. The few exceptions to this general rule are explained by the content of iron compounds of the soils (as indicated by their reddish color) or by the properties of the soil colloids. A similar relation between toxicity and soil texture has been noted by Cooper, *et al.* (*4* and *5*), Albert and Arndt (*2*), and Albert (*1*) working with South Carolina soils, and Reed and Sturgis (*11*), working with Louisiana soils.

The total arsenic content of a soil has not proved to be a satisfactory criterion of toxicity. As Vandecaveye, Horner, and Keaton (*15*) have shown, arsenic toxicity to barley is more closely correlated with the fraction soluble in 0.1 *N* ammonium acetate solution than with the fraction soluble in hot concentrated HNO_3. The results of Reed and Sturgis (*11*) show that the total arsenic content of the soil does not determine toxicity to rice. They indicate that toxicity is more closely correlated with arsenic soluble in 0.05 *N* HCl than with that soluble in water. According to Albert and Arndt (*2*), arsenic soluble in a collodion-bag dialysate is a reliable index of toxicity, whereas total arsenic is not. Greaves (*9*) has found no correlation between total and water-soluble arsenic in orchard soils.

Judging from other researches, not concerned directly with toxicity to plant growth, soils vary widely with respect to capacity for arsenic fixa-

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[2] This paper was made possible by the coöperative project on control of noxious weeds conducted by the California Agricultural Experiment Station and the Division of Cereal Crops and Diseases, Bureau of Plant Industry, United States Department of Agriculture.

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[5] Italic numbers in parentheses refer to "Literature Cited" at the end of this paper.

tion* and retention against leaching. In the work of Schulz and Thompson (*13*), sodium arsenite was readily leached from a Wisconsin forest soil. McGeorge (*10*), on the other hand, showed by lysimeter experiments that sodium arsenite was strongly held despite excessive leaching by certain Hawaiian soils; he also found that soils varied in their capacity to fix soluble sodium arsenite. According to Dratschew (*8*) also, soils vary in capacity for arsenic adsorption. Stewart (*14*) records further evidence of variation between soils, showing that water extracts of various soils differ markedly in their capacity for dissolving lead arsenate.

The general principle may therefore be advanced that toxicity is directly related to the water-soluble, the dilute-acid-soluble, or some similar fraction of the total arsenic. This holds true whether one is dealing with the native arsenic in an untreated soil or with the arsenic applied as a soluble or an insoluble salt. Applied to the relation between toxicity and textural grade, this principle leads one to suppose that in heavy soils less arsenic is water-soluble for a given application, than in light soils. Since the ability of some soils to fix arsenic is greater than that of others, one may explain the relation of toxicity to textural grade by assuming a greater fixation of soluble arsenic in heavy soils than in light. In the present work, this assumption was submitted to experimental test; that is, an attempt was made to determine whether or not the toxicity of sodium arsenite in California soils, measured by greenhouse tests already reported (*7*), could be explained by arsenic fixation.

METHODS

The greenhouse technique in the determination of arsenic toxicity has been described in detail in the previous paper of this issue (*7*, p. 181). Results obtained by the method outlined are also given for 80 California soils (*7*, *table 3*) as yield of tops, in grams fresh weight, of oat plants corresponding to various applications of sodium arsenite to the soil expressed as p.p.m. As_2O_3 on the basis of air-dry soil.

* In this paper the word *fixation* denotes the process of rendering soluble arsenic insoluble by contact with the soil. *Fixed arsenic is arsenic insoluble in water.* Both adsorption and chemical precipitation are included in this definition, the emphasis being placed entirely upon the extent of insolubility rather than the manner of its accomplishment.

This limited definition is necessary because the word *fixation* has had at least three different uses: first, it has been used to mean loss of availability to plants; second, loss of solubility; and third, retention against leaching. The present paper is concerned solely with the second of these meanings, and the previous paper (*7*) with the first. The term could therefore have been used in connection with either or both studies. To avoid ambiguity, the word was not used at all in the previous paper (*7*), and the specific definition given above adhered to in the present paper. This is purely a matter of convenience, and no claim is made that the "best" or most suitable use of the term has been attained.

Thirty-three of the 80 soils were chosen for the present study, a wide range of textural grades being selected. Toxicity curves were plotted for these 33 soils, the application of sodium arsenite expressed as p.p.m. As_2O_3 on the basis of oven-dry soil being plotted on the horizontal axis against the yield expressed as a percentage of the check, that is, of the yield without arsenic. The hygroscopic moisture content, which varied from about 0.5 to 8.0 per cent, was thus eliminated as a variable, and the curves all originated at the same height on the vertical axis. The data given in columns 4 and 5 of table 1 (p. 209) and in column 4 of table 2, (p. 213) were taken from the 33 curves thus produced.[7]

Arsenic fixation was measured in a series of standard laboratory runs conducted rigidly as follows:

Sodium arsenite stock solution was applied to samples of air-dry or moist soil equivalent to 100 grams of oven-dry soil. This solution, identical with the one used in the greenhouse tests, contained 5.00 grams As_2O_3 and 1.25 grams NaOH per liter. Enough water was added to make a total of 100 ml, including soil moisture and water added as sodium arsenite solution. Two samples of each of 6 different soils were handled in each run. One sample of each pair received a uniform application of arsenic; the other an application varying from soil to soil in a manner that will be explained.

The 12 soil and water mixtures thus prepared were agitated mechanically for 18 hours in 1-pint wide-mouthed jars by continuous rotation on the parallel shafts of a machine, and a portion of each was then filtered. Usually enough filtrate could be obtained under gravity, but sometimes filtration by suction was necessary. Some filtrates, especially those of sandy soils, were turbid. These were returned to the filter as often as necessary to get a clear solution. Occasionally some very fine suspended material remained despite these precautions.

The 1:1 extracts thus prepared were analyzed singly by the Gutzeit method (*3*, p. 306) within 2 hours of filtration,[8] without preliminary acid digestion or other treatment. An attempt was made to choose an aliquot for analysis that would yield approximately 0.015 mg As_2O_3, since this amount could be most accurately determined.

[7] These toxicity curves have not been published. Four examples of this type of curve are given in figure 5 (p. 226) of this paper, but the points plotted represent the means of 3 or 4 greenhouse tests. The toxicity data of tables 1 and 2 were taken from curves plotted from greenhouse results obtained simultaneously on 20 or 40 soils, each curve being derived from a triplicated test series on the soil concerned.

[8] According to tests, the arsenic content of extracts decreased markedly in some cases during periods of several days to a month. All extracts were therefore analyzed immediately after filtration. If the aliquot was poorly chosen, a new extract was prepared.

The directions for the Gutzeit method given by the Association of Official Agricultural Chemists (*3*, p. 306) were followed in detail with one exception: instead of maintaining the Gutzeit generator-bottle units at a constant temperature between 20° and 25° C for 1½ hours after addition of the zinc, the generator bottles were placed in an ice bath 10 minutes before the zinc was added and were held in it for 20 minutes after.[9] They were then removed and let stand at room temperature 1 hour before the stains were measured. Standard stains for 0.005, 0.010, 0.015, 0.020, and 0.025 mg As_2O_3 were prepared in duplicate for each run from the same Hanford-Pratt sensitized sheet used for the 12 soil-extract analyses. The paper sheets were sensitized by soaking 1 hour in 4 per cent mercuric bromide solution in 95 per cent alcohol.

All operations in the standard run described above were carried out in 2 days. The soil and water mixtures were customarily prepared in the pint jars in the afternoon and then agitated overnight. The filtrations were made the following morning, and the Gutzeit analyses completed the same day.

To calculate the percentage fixed, the difference between the concentration of arsenic applied and that found soluble was expressed as a percentage of the concentration applied. This value will be called the "apparent fixation," or "percentage fixed as determined."

Errors affecting the fixation values presented in this paper are as follows:

a) The inherent standard deviation of single analyses for arsenic by the Gutzeit method. This was determined by analyzing two different sodium arsenite stock solutions, of the composition given above, eighteen times each, and was found to be approximately ± 7 per cent for aliquots yielding 0.015 mg As_2O_3.

b) The effect of magnitude of fixation upon the accuracy of the fixation percentage. Since fixation was determined by difference in arsenic concentration of a solution before and after contact with the soil, the values for percentage fixed are subject to a sliding scale of error even though the standard deviation of the analysis itself remains constant. At a determined fixation of 0 per cent (the arsenic remaining 100 per cent soluble), the true fixation may lie anywhere between + 7 or —7 per cent; at 50 per cent fixed between 46.5 and 53.5; while at 100 per cent fixed the error is zero.

c) The effect of the soil extract upon the arsenic analysis. By attempting the recovery of 0.015 mg As_2O_3 in the presence of 1 ml or less[10] of 1:1 extract of several differerent soils, it was found that soil extract caused high results. Since the amount soluble as determined is thus too high, the percentage fixed as determined is too low and must be given an upward correction to compensate for this source of error.

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[9] The use of an ice bath was recommended by the California State Department of Agriculture Division of Chemistry.

[10] In the routine analytical work the aliquots taken were restricted to no more than 1 ml and were sometimes as small as 0.06. All aliquots less than 1 ml were secured by measuring relatively large volumes of diluted extracts.

From this discussion it should be apparent that all values for percentage fixed determined by the method above outlined are subject to an uncertainty which diminishes in the direction of high fixation. The fixation values tend to be too low because of the presence of soil extract.

Figure 1 shows an attempt to illustrate graphically the range within which the corrected fixation values are expected to lie.

In this diagram, the 33 soils are grouped into two classes. One class includes the fight soils which required 0.1 ml or less of extract[11] for an analysis. The tests on effect of extract show that the maximum error produced by any soil in this class was about + 9 per cent and the minimum + 3 per cent. An error of + 9 per cent combined

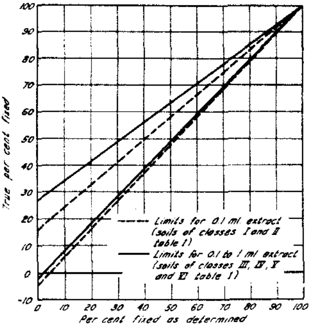

Fig. 1.—Apparent fixation, or percentage fixed as determined, plotted against the limits within which the true percentage fixed is expected to lie.

with + 7 per cent standard deviation gives a total of + 16 per cent. Negative corrections of 16 per cent in the *soluble* arsenic to compensate for this error would result in the series of *fixation* values given by the upper dotted line in figure 1. If the + 9 per cent error coincided with the negative value of the standard deviation, the net effect would be a + 2 per cent error. However, a lower limit based on corrections of —2 per cent is not plotted in figure 1 because only the limits for the entire group of soils are desired. Instead, the minimum error for the group of + 3 per cent is combined with a —7 per cent standard deviation for a net negative error of 4 per cent. Corrections of + 4 per cent in the soluble arsenic result in corresponding negative corrections in the fixation values; these are indicated by the lower dotted line in figure 1.

[11] As will become evident, the volume required depends on three factors: (*a*) application of arsenic; (*b*) time interval; (*c*) fixation. In the tests on effect of extract, the volumes chosen were those necessary to provide about 0.015 mg As_2O_3 with an application of 300 p.p.m. As_2O_3 and a time interval of 18 hours, these specifications applying to the data of table 1 (p. 209).

The limits indicated by solid lines apply to the balance of the soils, which require more than 0.1 and up to 1.0 ml of extract for an analysis. The maximum error in soluble arsenic due to extract in this group was + 20 per cent, the minimum + 5 per cent.

Statistical odds cannot be given for the expectation that the true values will lie between these limits. For soils midway between the extremes, with respect to effect of extract, the odds would be very high, and for soils near or at the extremes the odds would be lower.

RESULTS

Toxicity-Fixation Interrelation at 300 P.P.M. As_2O_3.—Table 1 presents data on toxicity, arsenic fixation, and soil moisture content at field capacity in 33 California soils. Of these soils, all but one, Yolo sand, are included in the group of 80 described in the preceding paper (*7*). Yolo sand is an infertile sand of practically no agricultural value deposited by the flood waters of Putah Creek.

The field capacities of the soils are given in column 3 of table 1.

The data on toxicity appearing in columns 4 and 5 were taken from the unpublished toxicity curves described in the section on "Methods." Column 4 gives for each soil the approximate application reducing the yield 95 per cent in the greenhouse test. Column 5 gives the area, in square centimeters, under each toxicity curve, measured with a planimeter. These areas are, of course, significant only on a relative basis, the absolute values being determined arbitrarily by the scales adopted in plotting the curves.

The data on arsenic fixation are given in columns 6 and 7. It was originally intended to compare the soils, as to percentage fixed, at a uniform application of 300 p.p.m. As_2O_3. The Gutzeit analyses of the sodium arsenite stock solution varied from run to run, however, and the actual applications were varied in an attempt to compensate for the supposed changes in concentration of the stock solution. It was learned later that these changes in concentration were not real, but were embraced by the inherent standard deviation of the analysis. As has been explained, the limits of error for the percentage fixed graphically presented in figure 1 include an allowance for the standard deviation.

In experiments referred to throughout the paper as the "first series," actual applications of sodium arsenite varied from 275 to 315 p.p.m. As_2O_3. To permit a valid comparison on the basis of 300 p.p.m. applied, slight corrections were made, where necessary, by interpolation. As previously stated, different applications of arsenic were made to two samples of each soil. Each was plotted against the corresponding percentage fixed, and a straight line drawn between these points. The fixation percentage

TABLE 1

Soil Type, Arsenic Toxicity, and Arsenic Fixation at 18 Hours, in 33 California Soils

Soil characteristics			Greenhouse results		Fixation measurements at an application equivalent to 300 p.p.m. As_2O_3	
Soil grouping based upon toxicity and fixation of arsenic	Soil type, soil series, and textural grade	Field capacity (H_2O) on basis of dry soil	Application causing 95 per cent reduction in yield (As_2O_3 basis)	Area under curve	Apparent fixation	Limits of expected deviation
1	*2*	*3*	*4*	*5*	*6*	*7*
		per cent	*p.p.m.*	*sq. cm.*	*per cent*	*per cent*
Class I, toxicity limits 50 to 150 p.p.m. (col. *4*); fixation limits 20 to 45 per cent (col. *6*)	Greenfield coarse sandy loam	17.4	95	5.5	22.4	19.0–35.0
	Fresno sandy loam	17.6	65	5.3	27.5	24.5–39.0
	Hanford sandy loam	27.0	140	9.7	39.3	37.0–49.0
	Hanford fine sandy loam	17.8	140	10.7	42.3	40.0–51.5
	Average for class I	19.9	110	7.8	32.9	30.0–43.5
Class II, indeterminate between I and III	Delano fine sandy loam	18.4	250	16.0	35.9	33.0–46.0
	Rocklin sandy loam	21.0	450	22.0	48.8	46.5–57.0
	Rositas fine sand	17.4	100	8.9	56.6	53.5–63.0
Class III, toxicity limits 250 to 450 p.p.m. (col. *4*); fixation limits 60 to 85 per cent (col. *6*)	Sierra sandy loam*	17.1	275	21.5	43.6	42.5–58.5
	Chino silty clay loam	25.5	250	22.9	64.3	63.5–74.0
	Columbia fine sandy loam	23.1	250	20.3	65.7	65.0–75.0
	Yolo fine sandy loam	19.8	525†	31.6	67.3	66.5–76.0
	Madera loam	15.6	425	25.0	70.3	69.5–78.5
	Yolo silt loam	23.5	300	22.3	71.8	71.0–79.5
	Yolo sand	18.2	325	29.3	72.1	71.5–79.5
	Yolo loam	25.4	300	26.2	74.4	74.0–81.5
	Yolo clay loam	35.9	350	27.0	80.5	80.0–86.0
	Yolo adobe clay‡	36.1	375	24.3	86.0	85.5–90.0
	Average for class III	24.0	337	25.0	72.5§	72.0–80.0
Class IV, indeterminate between III and V	Fresno light clay	32.9	550	21.1	60.2	59.5–71.0
	Arbuckle clay loam	23.3	500	34.7	77.8	77.0–83.5
	Stockton adobe clay	42.4	700	34.7	80.3	80.0–85.5
	Montezuma adobe clay	36.8	425	40.6	86.0	85.5–90.0
Class V, toxicity limits 500 to 700 p.p.m. (col. *4*); fixation limits 85 to 93 per cent (col. *6*)	Madera clay	32.5	600	38.9	85.1	84.5–89.0
	Sites adobe clay	28.9	625	36.9	86.9	86.5–90.5
	Yolo clay¶	34.0	900¶	30.8	87.5	87.0–91.0
	Sacramento clay loam	40.0	575	35.3	88.5	88.0–91.5
	Egbert loam	40.9	525	36.1	90.1	90.0–93.0
	Panoche adobe clay	34.2	600	44.2	90.9	90.5–93.0
	Imperial clay	35.4	650	45.4	92.5	92.5–94.5
	Average for class V	35.1	639	45.4	88.8	88.5–92.0
Class VI, toxicity limits 800 to 1,300 p.p.m. (col. *4*); fixation limits 93 to 99 per cent (col. *6*)	Sierra gravelly loam‖	15.8	825	64.9	91.4	91.0–93.5
	Merced adobe clay	62.3	1,100	68.8	94.0	94.0–95.5
	Anita adobe clay	36.3	900	56.9	94.9	94.5–96.0
	Dublin adobe clay	46.2	850	77.8	95.5	95.5–96.5
	Aiken clay loam	29.2	1,300	95.0	98.6	98.5–99.0
	Average for class VI	38.0	995	72.7	94.9	94.5–96.0

* Shows a very low rate of fixation; at the end of 7 weeks is about equal to Yolo adobe clay.

† Repeat greenhouse test gave 275 p.p.m. as the application producing 95 per cent yield reduction.

‡ Shows a very high rate of fixation and consequently has too high a relative position at 18 hours.

§ Does not include Sierra sandy loam.

¶ This soil might belong in class VI. A different greenhouse test, however, gave 650 p.p.m. as the application producing 95 per cent yield reduction.

‖ Being in the same series as Sierra sandy loam, this soil has probably a low rate of fixation. If so, it would have too low a relative position at 18 hours.

at 300 p.p.m. was taken from this straight-line graph. Column 6 gives the percentages fixed, *corrected to a uniform application of 300 p.p.m.*; column 7, the limits of deviation within which the true values of these fixations may be expected to lie, these limits having been taken from figure 1. As previously indicated, two sets of limits are included in figure 1. One set applies to the fixation data for the soils in classes I and II, table 1. These soils, which fix the least arsenic, permit Gutzeit analyses on 0.1 ml or less of 1 :1 extract at 18 hours with approximately 300 p.p.m. As_2O_3 applied. The other set of limits applies to the soils in the other four classes, which furnish 1 :1 extracts such that 0.1 to 1 ml is required for an analysis with the same time and application.

The correlation of textural grade with fixing power, toxicity, and field capacity is indicated by the grouping of soils into classes given in column 1. The soils in class I—all light soils—exhibit the greatest toxicity, the lowest fixation, and the lowest field capacity. One can best see these facts by comparing class averages. Although the soils of class II do not fit into either I or III as delimited, they are obviously nearer these classes than any other. They have therefore been designated as "indeterminate" between I and III. The soils of class III illustrate the fact that textural grade is not the only factor involved in arsenic toxicity. This class includes the soils of intermediate toxicity, fixing power, and field capacity, yet includes 4 sandy soils and 1 adobe clay, 3 of which belong to the Yolo series. As the preceding paper (*7*) indicates, the Yolo series is a poor one for present purposes of illustration. This series is of recent alluvial origin from original sedimentary sources, and all types display a high capacity for arsenic fixation.

At this point, attention may be drawn to the importance of the time factor. As will become evident, soils do not all display the same rate of fixation. Thus both Sierra sandy loam and Yolo adobe clay are indeterminate in ultimate fixing power, but the former fixes much less arsenic than the latter at 18 hours.

Class IV is again indeterminate between adjacent classes. Class V includes what might be called medium-heavy soils, although there is little, in terms of soil type, to distinguish it from class VI, which includes the soils of lowest toxicity, highest fixation, and highest field capacity. Three outstanding exceptions appear in the last two classes. Egbert loam is an organic soil. Sierra gravelly loam and Aiken clay loam are both red soils and, as has frequently been observed, possess arsenic- and phosphorus-fixing capacities beyond expectation in terms of textural grade.

The sharply delimited classes given in table 1 represent, however, only one of many possible groupings. Broader class limits would eliminate

some of the seven indeterminate soils; but one need not suppose that fixation and toxicity should be correlated in every instance when one considers that, up to the attainment of fixation equilibrium in time, other sets of fixation figures at other time intervals would doubtless give different relative as well as absolute results. Furthermore, as will become evident (p. 225), the rate of change of percentage fixation with change in application, with a fixed time interval, differs somewhat for different soils. Thus, had the soils been compared as to fixing power at some application other than 300 p.p.m., somewhat different relative as well as absolute results would probably have been obtained.

There is also the question as to which measure of toxicity is best. In the preceding paper (7), the relative toxicity of arsenic in 80 soils was made evident by arranging the yield data in a regular order according to textural grade of the soil. The toxicity curves, previously described, in which percentage yield is plotted against application (on the basis of dry soil), provide a means of more accurate comparison. At least four methods, however, may be used to obtain a measure of toxicity from the curves. One may (1) determine the applications producing some given percentage reduction in yield; (2) measure the areas under the curves as expressing an average toxicity over the entire effective range of applications; (3) determine the percentage reductions in yield caused by some given application; or (4) measure the slopes of the curves at some fixed place. The class limits set in column 1 of table 1 were determined on the basis of the application causing a 95 per cent yield reduction. This criterion of toxicity was used because it is the most practical in terms of soil sterilization. Though a yield reduction of 100 per cent is, of course, the ideal, the application for this point cannot well be determined accurately because of the increasingly gentle slope of the curves as they approach the base line.

The area under the curve is apparently an inverse measure of average toxicity over the entire range of applications; and although this average toxicity might be of considerable theoretical interest in some cases, it has less practical importance than a determination of the application necessary to sterilize the soil.

Methods 3 and 4, mentioned above, were also tried. A determination of the yield reductions resulting from an application of 200 p.p.m., for example, provides a set of figures ranging from 100 per cent in some of the soils in class I to as low as 5 per cent in one of the soils in class VI. The determination of the slopes of the curves does not provide a generally satisfactory basis for estimating toxicity because the general trend of a curve may not be correctly indicated by a particular segment of it.

In most cases the two measures of toxicity given (table 1, cols. 4 and 5) substantially agree. In some cases they do not, however. Thus, with Fresno light clay and in similar cases, a disproportionately large application is required to accomplish the last 10 or 15 per cent of yield reduction necessary to the total of 95.

Finally, one must realize that the greenhouse runs could not all be made at the same time and that if the tests were repeated on all 33 soils, differences in relative results might occur. Repeated runs on several soils are reported in the previous paper (7).

Toxicity-Fixation Interrelation at Approximately 50 Per Cent Yield Reduction.—Besides the first series of applications at approximately 300 p.p.m., another set, hereafter called the "second series," was made in connection with the fixation studies. The actual applications are tabulated in column 3 of table 2, and the reduction in yield corresponding to each appears in column 4. The reductions recorded vary between 40 and 60 per cent. In seven cases where the reductions were beyond these limits, the data are omitted.

Column 5 gives the apparent fixation, or the percentage fixed as determined, at each of the recorded applications; column 6 the limits of deviation within which the true values are expected to lie. These limits (taken from fig. 1) were originally determined for applications of about 300 p.p.m. The applications in the second series were usually, however, less than this, and the average aliquot of extract necessary for an analysis was 0.74 ml as opposed to 0.33 ml for the first series of applications of 300 p.p.m. Despite this circumstance, the limits of deviation for applications of about 300 p.p.m. provide a generally satisfactory basis for evaluating the fixation data of table 2 because the limits were set to allow for extreme effects of extract. To illustrate, an upper limit of + 20 per cent was set for the error due to extract in all classes except I and II. The extracts of many of the soils in these classes, nevertheless, would not have produced so great an error even with much larger aliquots than were actually used.

An independent consideration of the relation between toxicity and fixation is afforded by the data of column 7. Here the concentrations of soluble arsenic at 100 per cent moisture, time interval 18 hours, are recorded for each soil at a series of applications giving approximately the same biological result (40 to 60 per cent reduction of yield). The class averages in this column reveal no clearly significant difference between any one class and another, which suggests that when fixation is allowed for, all soils are alike with respect to the concentration of soluble arsenic required for a given degree of toxicity. In interpreting these data, one

TABLE 2

ARSENIC FIXATION AT APPLICATIONS CAUSING YIELD REDUCTIONS OF APPROXIMATELY 50 PER CENT

Soil grouping	Soil type	Applications of arsenic (As_2O_3 basis), on basis of dry soil	Reduction in yield	Arsenic fixation measurements: As determined	Arsenic fixation measurements: Limits of expected deviation	Soluble arsenic (As_2O_3 basis) in 1:1 extract, limits of deviation
1	2	3	4	5	6	7
		p.p.m.	per cent	per cent	per cent	p.p.m.
Class I	Fresno sandy loam	25	41	40.0	37.5–49.5	15.6–12.6
	Hanford sandy loam	45	48	47.8	45.5–56.0	24.5–19.8
	Hanford fine sandy loam	57	48	56.9	55.0–64.0	25.6–20.5
	Average for class I	42	46	48.2	46.0–56.5	22.7–18.3
Class II	Delano fine sandy loam	95	58	52.8	51.0–60.5	46.5–37.5
	Rocklin sandy loam	72	41	64.7	63.0–70.5	26.6–21.2
	Rositas fine sand	55	50	55.5	53.5–63.0	25.6–20.3
Class III	Sierra sandy loam	115	46	56.5	55.5–68.0	51.2–36.8
	Chino silty clay loam	120	40	72.0	71.5–79.5	34.2–24.6
	Madera loam	155	53	79.0	78.5–85.0	33.3–23.2
	Yolo silt loam	105	40	78.4	78.0–84.5	23.1–16.3
	Yolo sand	137	40	82.5	82.0–87.5	24.7–17.1
	Yolo loam	137	40	82.0	81.5–87.0	25.3–17.8
	Average for class III	128	43	78.8*	78.0–84.5	26.2–19.8
Class IV	Fresno light clay	65	53	62.8	62.0–72.5	24.7–17.9
	Arbuckle clay loam	250	60	80.0	79.5–85.5	51.2–36.2
	Stockton adobe clay	130	45	89.5	89.0–92.5	14.3– 9.7
	Montezuma adobe clay	237	54	87.7	87.0–91.0	30.8–21.3
Class V	Madera clay	145	52	91.2	91.0–93.5	13.0– 9.4
	Sites adobe clay	155	45	92.7	92.5–94.5	11.6– 8.5
	Yolo clay	427	45	84.6	84.0–89.0	68.3–47.0
	Egbert loam	152	45	92.7	92.5–94.5	11.4– 8.4
	Panoche adobe clay	227	53	91.8	91.5–94.0	19.3–13.6
	Imperial clay	210	42	95.5	95.5–96.5	9.4– 7.3
	Average for class V	219	47	91.4	91.0–93.5	19.7–14.2
Class VI	Sierra gravelly loam	295	40	91.5	91.0–94.0	26.5–17.7
	Merced adobe clay	325	45	93.2	93.0–95.0	22.7–16.2
	Anita adobe clay	277	51	95.5	95.5–96.5	12.5– 9.7
	Dublin adobe clay	502	53	94.0	94.0–95.5	30.1–22.6
	Average for class VI	350	47	93.5	93.5–95.5	22.7–15.7

* Does not include Sierra sandy loam.

must again consider differences in rates of fixation; and since the toxic effect of the arsenic is being registered over a period of a month, one could not well specify a time interval that would be best from the biological standpoint. The effect of differences in moisture content at field capacity will be considered in a later section (see footnote 17, p. 225). At this point, suffice it to state that such differences apparently have less effect than might be expected.

The Time Factor in Fixation.—Table 3 gives the results of fixation measurements at approximately 7 weeks on samples of 9 of the 33 soils listed in table 1. Measurements on 4 of the same 9 samples at approximately 16 weeks, made in connection with another experiment (see fig. 3, p. 219), are also included. The soil samples used originated in standard greenhouse tests described on page 217 in connection with table 4. In the series from which the samples were obtained, each application of arsenic to the soil was replicated four times, and each can was watered daily. The cans were let stand in the greenhouse without watering for 2 days

TABLE 3

ARSENIC FIXATION AT 18 HOURS AND APPROXIMATELY 7 AND 16 WEEKS, AT AN APPLICATION EQUIVALENT TO 340 P.P.M. As_2O_3

Soil	Apparent fixation, 18 hours	Approximate 7-week interval		Approximate 16-week interval	
		Actual period	Apparent fixation*	Actual period	Apparent fixation
	per cent	*days*	*per cent*	*days*	*per cent*
Fresno sandy loam	25.7	46	72.4	105	74.5
Yolo adobe clay	85.0	54	89.4	116	90.4
Sierra sandy loam	40.8	54	87.9	119	93.3
Yolo clay	86.6	54	98.5	111	98.9
Greenfield coarse sandy loam	19.5	46	73.2	...	....
Delano fine sandy loam	32.5	46	72.4	...	....
Sacramento clay loam	87.6	49	99.8	...	....
Egbert loam	89.7	49	99.9	...	....
Sierra gravelly loam	91.0	54	99.4	...	....

* The original data on soluble arsenic, from which these fixation percentages were computed, are given in table 5 for 4 soils. In table 5 the application of 340 p.p.m. is arbitrarily called "treatment 1."

after the oat plants were harvested at the end of the standard 30-day growth period. The contents of the 4 cans were then combined, thoroughly mixed, and stored in a sealed Mason jar. The application of sodium arsenite at a rate equivalent to 340[12] p.p.m. As_2O_3 was taken in all 9 cases. As moisture determinations showed, the sandy soils had fallen to about 50 per cent of field capacity, and the others had decreased to about 85 per cent. Fixation measurements were made according to the standard procedure previously outlined in the section on "Methods," the moist equivalent of 100 grams of dry soil being taken for each extraction. For comparison, the fixation percentages at 18 hours are also included. These were corrected to the basis of 340 p.p.m. As_2O_3 applied by the method previously outlined (p. 208) for correction to 300 p.p.m.

[12] Cultures were established in the greenhouse tests containing 0, 15, 40, 80, 140, 220, 340, 490, 680, and 920 p.p.m. As_2O_3, on the basis of oven-dry soil.

The errors in the measurement of arsenic fixation were somewhat greater than in the tests reported in tables 1 and 2. Limits of deviation for the fixation percentages cannot be given because the limits set forth in figure 1 apply only to aliquots of extract yielding approximately 0.015 mg As_2O_3. Because of the positive error arising from the presence of soil extract, all aliquots were restricted to a total of 1 ml regardless of concentration. As fixation increases with time, the amount of arsenic in the 1-ml aliquot often falls considerably below 0.015 mg As_2O_3, especially with heavy soils and small applications. In these cases the limits of deviation, if determined, would be somewhat farther apart than those given in figure 1.

Another possible source of error is the absorption of arsenic by the oat plants. Crafts and Kennedy (*6*) have shown, however, that the lethal concentration of arsenic in morning-glory is approximately 0.02 per cent As_2O_3 on the dry basis, in the tops, and 0.0003 in the roots (*6*, p. 339). With the higher of these figures as a basis of approximate calculation, and the highest yield recorded in the present cultures of oat plants (8.6 grams fresh weight), roughly 0.3 mg As_2O_3 would be absorbed if the root system weighed half as much as the tops, and the average content of dry matter were 10 per cent of the fresh weight. Since most of the cultures contained the moist equivalent of 500 grams of dry soil, about 0.6 p.p.m. As_2O_3 would be absorbed. The decrease in concentration of soluble arsenic would be less than this, however, due to replacement of part of the absorbed arsenic from the solid phase. Even though the arsenic tolerance of oats might be much greater than that of morning-glory, arsenic absorption would evidently not cause errors beyond the limits of error of the method itself.

Table 3 thus shows that arsenic fixation in Sierra sandy loam is approximately the same as in Yolo adobe clay at 7 and 16 weeks, although widely different at 18 hours. Yolo adobe clay shows a very slight increase in fixation after 18 hours, whereas Sierra sandy loam has apparently not accomplished all its ultimate fixation at the end of 54 days. Of the four soils studied at the longest interval, only Sierra sandy loam increased significantly in fixation after about 7 weeks.

Besides the results in table 3 other data on the effect of time are shown graphically in figure 2. In these experiments, the air-dry samples of soil were given enough total water to make 1:1 extracts at the start of the tests, as in the procedure for the 18-hour fixation tests. The arsenic application was equivalent to 250 p.p.m. As_2O_3 on the basis of oven-dry soil. The jars containing the arsenic-treated soils at 100 per cent moisture were let stand, with occasional shaking, at laboratory temperatures for

the intervals indicated, one jar for each point on each curve. The extracts were analyzed singly by the Gutzeit procedure as outlined. Comments in the preceding paragraph concerning limits of deviation for the fixation percentages apply here as well. The experiment was performed during June, July, and August, 1937. For comparison, the approximate 7-week

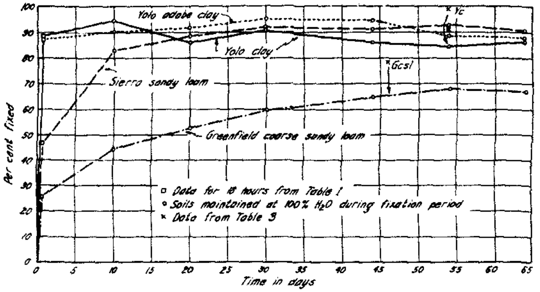

Fig. 2.—Time curves for Greenfield coarse sandy loam, Sierra sandy loam, Yolo adobe clay, and Yolo clay. All fixation percentages based upon an arsenic application of 250 p.p.m. As_2O_3 on the basis of dry soil.

fixation figures (table 3), corrected to a basis of 250 p.p.m. As_2O_3 applied, are plotted. Also the 18-hour figures, similarly corrected, are included as the first point on each curve.

These curves show that pronounced differences in rates of fixation do not appear after the first 10 days, even though differences in absolute level of fixation may exist throughout.

Whereas the 54-day points from table 3 for Sierra sandy loam and Yolo adobe clay lie fairly close to the curves, the 46-day point for the Greenfield coarse sandy loam appears to be significantly high, and the 54-day point for Yolo clay is unquestionably high at 99.2 per cent as opposed to 84.6 per cent on the curve. The points from table 3 represent fixation in soils held at field capacity or less, while the other points in figure 2 represent soils held at 100 per cent moisture. Apparently Greenfield coarse sandy loam and Yolo clay fix less arsenic from the 1:1 mixture than when held at a lower moisture content.

Relation of Moisture Content to Toxicity and to Arsenic Concentration.—Table 4 gives the results of standard greenhouse toxicity deter-

minations on 8 of the 9 soils[13] listed in table 3, along with the results obtained when the cans of soil were watered daily so as to maintain more nearly a constant percentage of moisture at field capacity. The tests were performed during February and March, 1937, after the original greenhouse work on arsenic toxicity in 80 California soils had been completed. They were intended to check the greenhouse results in the 9 soils selected, and also to measure the effect of the less-frequent watering practiced in the standard greenhouse runs. In the standard series, each application was duplicated, and the cans were watered whenever the plants showed

TABLE 4

GREENHOUSE DETERMINATIONS OF ARSENIC TOXICITY UNDER DAILY AND UNDER LESS-FREQUENT WATERING

Soils	Arsenic application (As_2O_3 basis) giving 95 per cent yield reduction	
	Watered daily	Watered 5 times during 30-day growth period
	p.p.m.	*p.p.m.*
Fresno sandy loam	135	135
Greenfield coarse sandy loam	200	200
Sierra sandy loam	200	150
Delano fine sandy loam	250	250
Yolo adobe clay	335	335
Yolo clay	650	800
Sacramento clay loam	900	900
Egbert loam	1,000	1,000

signs of wilting. This amounted to five times during the 30-day growth period. In the other series, each application was made in quadruplicate, and each can was brought to field capacity by weight each day.[14] As in the toxicity tests reported in table 1, curves were plotted relating the yield of tops, expressed as a percentage of the check, to the application of sodium arsenite as p.p.m. As_2O_3 on the basis of oven-dry soil. From these curves the applications causing a 95 per cent reduction in yield were determined as given in table 4.

Table 4 shows that in 6 cases out of 8 the results (toxicities) were identical under the two treatments, while in one case (Sierra sandy loam),

[13] Unfavorable physical condition of the soil made it impossible to get a uniform original stand of oats on Sierra gravelly loam. The results for this soil were therefore omitted as unreliable.

[14] The soil samples from two different applications for each soil in the series watered daily were saved at the end of the run, and utilized for the fixation measurements reported in table 3 at approximately 7 and 16 weeks.

the toxicity was higher with less frequent watering, and in another (Yolo clay) it was lower. Although the moisture content obviously fluctuated to some extent even in the cans watered daily, the fluctuation was much less than in the series watered only five times, wherein the moisture content undoubtedly fell to a point near the permanent wilting percentage between waterings. The fact that the toxicity was substantially unaffected by this marked decrease in moisture content suggests that the concentration of arsenic failed to increase as the moisture content diminished.

An attempt was made to secure experimental evidence on this point by determining the effect of varying the amount of water in the extract upon the concentration of soluble arsenic. Four soils of contrasting type were studied—Fresno sandy loam, Sierra sandy loam, Yolo adobe clay, and Yolo clay. The samples employed were the same ones used in the fixation tests at approximately 7 weeks reported in table 3. The extraction ratio tests were performed about 16 weeks after the arsenic was applied. During the period between these experiments, the soils were kept in sealed Mason jars at room temperatures. The tests were performed according to standard procedure, the moist equivalent of 100 grams of dry soil being taken for each extraction, and the extract being agitated 18 hours before being filtered and analyzed. The soil samples used were those originally given an application equivalent to 340 p.p.m. As_2O_3 (on the basis of oven-dry soil). Each experimental determination of concentration is plotted as a point in figure 3. The results with an extraction ratio of 1:1 (100 per cent water) were used to calculate the fixation percentages given in table 3 for approximately 16 weeks.

The curves of figure 3 were calculated in each case from the two experimental points marked by arrow; the adsorption equation used will be described in the next section, headed "Calculations." Each curve was extended to the moisture content at field capacity, but the lowest moisture contents reached experimentally were about twice field capacity.

For purposes of discussion, the following statement is given of the four general types of behavior which may occur when the moisture content of a soil is decreased.

1. The concentration of the given ion may rise in inverse proportion to the decreasing moisture content as, for example, with nitrate.

2. The concentration may rise but to a smaller extent than in 1. This is typical of ions which are adsorbed.

3. The concentration may remain practically constant. This is typically true with slightly soluble salts which provide a saturated solution over a wide range of moisture contents.

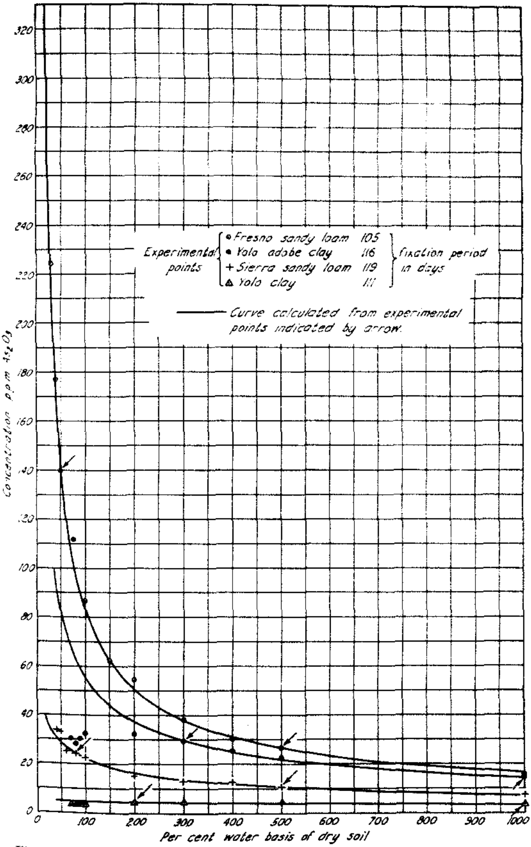

Fig. 3.—Concentration of soluble arsenic at various moisture contents for Fresno sandy loam, Sierra sandy loam, Yolo adobe clay, and Yolo clay. Application of sodium arsenite equivalent to 340 p.p.m. As_2O_3 on the basis of dry soil.

4. The concentration may decrease. This would happen in a mixture of slightly and readily soluble salts containing a common ion. For example, with calcium phosphate and calcium nitrate, a decrease in moisture content would increase the calcium ion concentration, and this in turn would result in a decrease in phosphate ion concentration owing to the operation of the solubility-product principle.

Behavior 1 is evidently not involved in the present study, but the other types are:

Fresno sandy loam and Sierra sandy loam constitute examples of behavior 2 over the range of moisture contents studied, as judged by the fact that the experimental points fall on or near the adsorption curves (fig. 3).

From 1,000 per cent to about 300 per cent water, Yolo adobe clay follows the adsorption curve but thereafter tends to follow first behavior 3 and then 4.

Yolo clay follows the adsorption curve fairly closely as plotted (fig. 3), but if a larger vertical scale were used, it would be seen that behavior 4 occurs between 200 per cent and 100 per cent water, and that behavior 3 apparently occurs between 100 per cent and 70 per cent. With this soil, however, the distinction between 2 and 3 is virtually nonexistent because the adsorption curve itself is practically a straight line with a very slight slope.

Returning to the toxicity data of table 4: clearly, with soils displaying behavior 3 or 4, no increase in toxicity would be expected as a result of a decrease in moisture. True, in table 4 the decreases in moisture content were in the range of field capacity or less, but if one may judge from the trends of the points in figure 3 for Yolo adobe clay and Yolo clay, an increase in arsenic concentration would not occur as the moisture content decreased. In the cases of Fresno and Sierra sandy loams, the application of 340 p.p.m. As_2O_3 is respectively beyond and at the upper limit of the sublethal range of applications. This is brought out in the toxicity curves of figure 5 (p. 226).

As will be shown in the next section in considering figure 4, the increase in concentration with decreasing moisture is far less than in figure 3 over the sublethal range of concentrations even though the behavior is dominantly one of adsorption. This principle is well illustrated by Yolo clay. With this soil, an application of 340 p.p.m. causes a reduction in yield of 63 per cent (fig. 5), which places this application in the sublethal range. The adsorption curve is so nearly flat that there would be no appreciable increase in concentration with a decrease in moisture even though adsorption were the dominant process.

CALCULATIONS

Curves relating the percentage yield to the concentration of arsenic in the soil solution would theoretically be alike for soils of different texture if fixation were the dominant factor in toxicity. Experimental data secured were not sufficient to permit an estimate of the concentration of soluble arsenic at each of the 9 applications used in the greenhouse tests. Given experimental measurements of concentration at 2 different applications, however, it is possible to calculate concentrations at other applications. The object of this section of the paper is to demonstrate these calculations, and to present curves of percentage yield against concentration of soluble arsenic resulting from them.

The equation[15] used was,

$$\log C = -\tfrac{3}{2} \log (F - x) + \log K,$$

wherein C signifies the concentration of soluble arsenic (p.p.m. As_2O_3), x the amount of arsenic in mg As_2O_3 fixed by 1,000 grams of dry soil, and F and K are constants. In the method of calculation used, F was first calculated from the following relations:

$$\log C_1 = -\tfrac{3}{2} \log (F - x_1) + \log K \text{ and}$$

$$\log C_2 = -\tfrac{3}{2} \log (F - x_2) + \log K. \text{ Subtracting:}$$

$$\log C_1 - \log C_2 = -\tfrac{3}{2} [\log (F - x_1) - \log (F - x_2)] \text{ and}$$

$$\log \frac{C_1}{C_2} = -\tfrac{3}{2} \log \frac{F - x_1}{F - x_2} \quad \text{and}$$

$$-\tfrac{2}{3} \log \frac{C_1}{C_2} = \log \frac{F - x_1}{F - x_2}. \text{ Therefore}$$

$$\log \frac{F - x_1}{F - x_2} = \tfrac{2}{3} (\log C_2 - \log C_1).$$

One can easily calculate the numerical value of the quantity, $\tfrac{2}{3}(\log C_2 - \log C_1)$, from the values of C obtained at the two different applications of arsenic made, letting C_2 be greater than C_1. If the antilog of $\tfrac{2}{3}(\log C_2 - \log C_1)$ be set equal to a, then

$$a (F - x_2) = F - x_1,$$

and from this,

$$F = \frac{a x_2 - x_1}{a - 1}.$$

Also,

$$F = x_2 + \frac{x_2 - x_1}{a - 1},$$

and the latter expression is more convenient to use.

Having measurements of C at 2 different applications, it is then possible to locate 2 points on, and hence determine, the straight-line curve of $\log C$ against $\log (F - x)$.

[15] The writers extend thanks to Dr. Herbert S. Zuckerman, who suggested this equation and assisted with the calculations.

If 1:1 extracts are used, x is equal to $A-C$, where A is the application as mg As_2O_3 per 1,000 grams of dry soil. Once the curve is plotted, as many C, x pairs as desired may be obtained from it. If it is desired to determine A corresponding to various values of C, the general formula is:

$$A = x + \frac{CW}{1{,}000},$$

wherein W signifies the volume of water in ml associated with 1,000 grams of dry soil. Thus, in a 1:1 extract, W is equal to 1,000 and A is equal to $x + C$. Curves of A against C at any other moisture content may be easily obtained by substituting the desired value of W.

If measurements of C are available at 2 different moisture contents, A held constant as in figure 3, it is again possible to plot the straight-line curve of log C against log $(F-x)$. In this case

$$x = A - \frac{CW}{1{,}000}.$$

W corresponding to various values of C may be determined from the formula,

$$W = \frac{1{,}000\ (A - x)}{C}.$$

This is the method which was employed in constructing the adsorption curves of figure 3, the experimental C, W pairs used being marked by arrow. These points were chosen by inspection. The shape of the curves would be little affected by the particular pairs chosen except in the case of Yolo adobe clay. The determinations in the latter case reveal a change in trend below 300 per cent water; and the points marked by arrow were therefore chosen to fit the determinations down to this percentage.

Figure 4 gives the calculated curves[16] of C against A for the same four soils that were used in figure 3. All curves represent C at 100 per cent moisture ($W = 1{,}000$) except two of the curves for Fresno sandy loam, which were calculated to field capacity (17.6 per cent) and to the lowest extraction ratio reached experimentally in figure 3 (30 per cent). The calculations were based on the fixation data for approximately 7 weeks given in full for the 4 soils concerned in table 5. This table includes the original data from which the fixation percentages in table 3 at 340 p.p.m. were calculated. Applications listed under treatment 2 varied from soil to soil, being usually chosen as near as possible to the applications listed in table 2 (p. 213); the samples for these determinations were handled as described on page 214 in connection with table 3.

The justification for calculating these curves lies in the fact that the

[16] The sharp break in the curves at values of A of about 5 p.p.m. is due to the fact that, according to the equation, there is a low value of C for each soil at which x becomes equal to zero. At values of C below this point, x becomes negative. Since a negative x has no reality significance, the curves were continued to the origin as straight lines from the point at which $x = 0$. It was not determined experimentally whether this part of the curves is correct, but if incorrect, the effect would be to make the values of C slightly too high at low values of A.

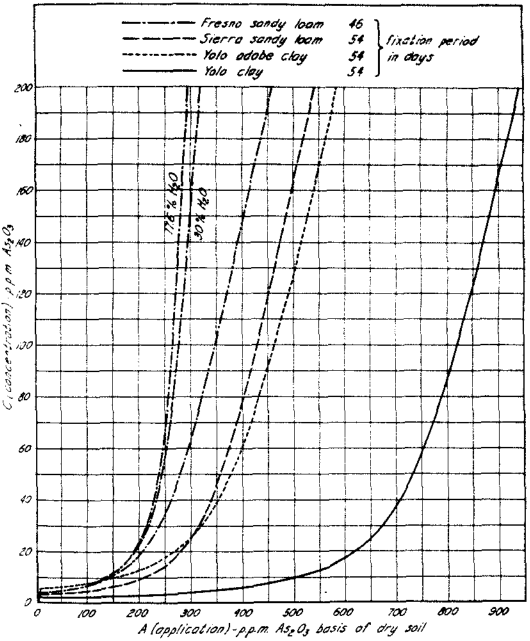

Fig. 4.—*A* (application) plotted against *C* (concentration) at 100 per cent water except as noted. Calculations based on fixation data at approximately 7 weeks given in table 5.

equation used was satisfactory in figure 3 wherever behavior 2 (adsorption) was involved. The fundamental relation is the change of x with C, and this can be tested either by varying A, the application, or W, the water content.

Regarding the time interval of approximately 7 weeks, it is clear that no interval could be defended as theoretically best, since the final greenhouse yields are related to the net effect of arsenic over a period of 30

days. The 7-week interval was chosen because, as figure 2 has indicated, a period of at least 10 days is preferable to 18 hours, and the 7-week interval was the next available. The latter, as is also evident from figure 2, gives about the same results as would be obtained at 30 days.

The values of *C* were calculated to 100 per cent water because this procedure was thought to give the best general approximation of the concentrations in the soil solution. Three points are involved: (*a*) with behavior 3 dominant, 100 per cent is best because the experimental measurements were made at this moisture content (1:1 extracts used); (*b*)

TABLE 5

VALUES OF *C* (CONCENTRATION) AND *A* (APPLICATION) AT APPROXIMATELY 7 WEEKS

Soil	Actual length of period	Application (As_2O_3 basis)		Concentration of As_2O_3 (*C*) 1:1 extract
		Treatment No.	Rate (*A*) on basis of dry soil	
	days		*p.p.m.*	*p.p.m.*
Fresno sandy loam	46	1	340	94.0
		2	40	4.8
Sierra sandy loam	54	1	340	41.0
		2	140	6.2
Yolo adobe clay	54	1	340	36.0
		2	140	9.5
Yolo clay	54	1	340	5.1
		2	680	31.6

with behavior 4, the moisture content at which the experimental determinations were made is again the best, since the use of a lower value would involve a calculated increase in place of an actual decrease in concentration. If the decrease is not great, the values at 100 per cent water may be a close approximation to those in the soil solution. Yolo adobe clay is the only soil of the 4 studied in which behavior 4 might be of practical moment, and in this soil (fig. 3), the trend of the experimental points below 100 per cent water, while apparently downward, appears somewhat erratic; (*c*) with behavior 2, the increase in concentration in going below 100 per cent water is negligible over most of the range of sublethal applications. This point is well illustrated by Fresno sandy loam. The standard toxicity curve for this soil in figure 5 shows that only 3 per cent of the check yield is obtained at an application equivalent to 140 p.p.m. As_2O_3. Figure 4 shows that with *A* equal to 140 p.p.m., *C* is

equal to 10 p.p.m. at 100 per cent water, and 11 p.p.m. at both 30.0 and 17.6 per cent, the curves for the last-mentioned moisture contents having merged at a value for A of about 175 p.p.m. At all sublethal applications below 140 p.p.m., it evidently makes no practical difference which curve is taken. At an application of 220 p.p.m., however, there is still a 1 per cent yield (fig. 5), which places this application roughly at the upper end of the sublethal range, and at this point C increases from 24 to 35 in going from 100 per cent to field capacity. Thus, at the very lowest percentage yields, the values of C at 100 per cent water may be somewhat too low with soils showing behavior 2.[17]

Thus the curves of figure 4 apparently represent an approximation of the relation between the application, A, and the concentration, C, in the soil solution at the end of the greenhouse growth period. They may therefore be used to replot the toxicity curves of figure 5 on the basis of C, as above qualified, instead of A. Figure 6 gives the curves on this basis, the value of C corresponding to A for each percentage yield being taken from figure 4. Figures 5 and 6 are plotted on the same scale, and it is at once evident that the outstanding differences between the curves in figure 5 are absent in figure 6. This suggests that differences in fixation are largely responsible for the original differences between soils of different textural grades.

Although, as above noted, fixation appears to be the dominant factor in toxicity, attention may be drawn to the fact that the curves of figure 6 are not identical, a considerable divergence appearing between them below yields of approximately 30 per cent. This suggests the possibility that the concentration of water-soluble arsenic is not the only factor which may influence toxicity. If part of the insoluble or fixed arsenic were, for example, available in the case of the two sandy loams, the divergence between the curves would be largely accounted for. Part of the insoluble nutrient elements are of course known to be available in the soil, and it may be that because of replacement, less intense fixation, or other causes, some of the insoluble arsenic in certain soils may be effective biologically.

As mentioned on page 211, a comparison of soils as to fixing power at any given application is subject to the criticism that at other applications other relative as well as absolute results might prevail. This is illustrated in figure 4 by the crossing of the curves for Sierra sandy loam and Yolo

[17] Points *a*, *b*, and *c* above indicate that the concentrations given in column 7 of table 2 at 100 per cent water represent an approximation of the concentrations in the soil solution. Roughly equal toxicities are thus associated with roughly equal average concentrations for four different classes of soils, suggesting that the soils would be alike in field and greenhouse toxicity if it were not for differences in fixing power.

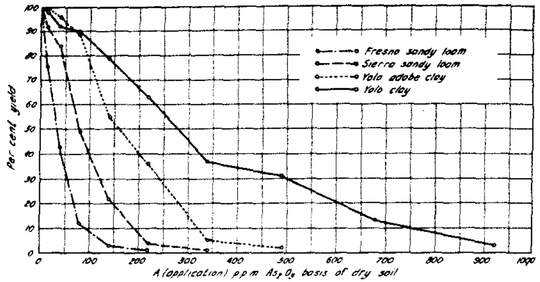

Fig. 5.—Percentage yields plotted against applications of arsenic to the soil for Fresno sandy loam, Sierra sandy loam, Yolo adobe clay, and Yolo clay, each point representing the mean of 3 or 4 greenhouse runs.

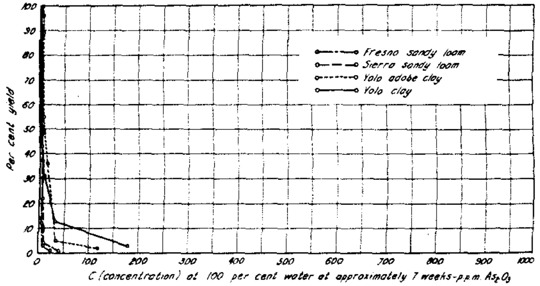

Fig. 6.—Same percentage yields as in figure 5 plotted against the calculated concentrations of arsenic at 100 per cent water taken from figure 4.

adobe clay at an application of about 305 p.p.m. Below this application, Sierra sandy loam would show the greatest percentage fixation, while above it the relation would be reversed, as shown in table 3 at approximately 7 weeks and an application of 340 p.p.m. Reversals in rank would undoubtedly occur in some cases in table 1 if comparisons were made at an application other than 300 p.p.m. Apparently, however, these reversals would involve minor shifts in position. Some of the present inconsistencies might be resolved and others accentuated, but apparently the broad relation between toxicity and fixation would be unaffected.

GENERAL DISCUSSION

The data presented in this paper lead to several general conclusions. First, different soils fix different percentages of a given application of arsenic. Second, the light soils of relatively low moisture-holding capacity, in general, fix least, and the heavy soils of high moisture-holding capacity fix most arsenic. Several exceptions are noted. Thus the red soils appear to have a high fixation capacity, apart from textural grade, because of their iron content, whether this be a chemical or physical or mixed effect. The one organic soil tested proved to have a high fixing power, though of medium textural grade. Third, as above qualified, light soils require less arsenic to sterilize them than do heavy soils. In a general sense, therefore, toxicity is inversely related to fixing power. Fourth, moisture content at field capacity is not important in determining toxicity. Thus the light soils display, on the whole, the greatest toxicity because they fix least arsenic, not because they hold little water. Fifth, considerable differences appear in the rates at which different soils fix arsenic.

With these broad conclusions in mind, one sees that the concentration of water-soluble arsenic serves as a general indicator of toxicity. As mentioned in the Introduction, other investigators (*15, 11, 2*) have suggested that the 0.1 *N* ammonium-acetate-soluble, the dilute-acid-soluble, and the dialyzable arsenic are each closely correlated with toxicity. Also (p. 225), as the present authors have indicated, part of the fixed or insoluble arsenic may be effective in causing toxicity. Judging from these observations, in the field of arsenic toxicity, as in the study of mineral nutrition, the question of "availability" is complex; in the present state of knowledge, one cannot state which fractions of the total arsenic should be considered strictly responsible for toxicity effects. The replacement of adsorbed phosphate by other anions occurs, as shown by Scarseth (*12*) and others; and Cooper, *et al.* (*4*) have observed in the field that arsenic toxicity is greatly increased by treatment with soluble phosphates. All that can be said is that toxicity is more closely correlated with water-soluble arsenic than with total arsenic, and that other fractions, more closely related to water-soluble than total, may also correlate with toxicity.

The data bearing on the effect of the amount of water upon concentration indicate that one should not use an unnecessarily large amount of water in making a soil extract for purposes of determining arsenic solubility if the results are to be reported on the basis of dry soil. Data at any convenient extraction ratio may serve certain purposes of comparison

within the limits of a given investigation, but the results obtained with 1:10 extracts by Reed and Sturgis (*11*), for example, are not comparable with those obtained with 1:5 extracts by Vandecaveye, Horner, and Keaton (*15*), or with those obtained with 1:1 extracts reported here, even though all are given on the basis of dry soil.

With behavior 2, 3, or 4, as described on pages 218–20, an erroneously high result will be obtained by multiplying the observed concentration by a factor equivalent to the extraction ratio, and the higher the ratio the greater the error.

SUMMARY

With certain exceptions, notably the red soils, light soils fix the lowest, and heavy soils the highest, percentage of a given application of sodium arsenite.

Light soils require the least and heavy soils the most arsenic to sterilize them. Toxicity is thus inversely proportional, in general, to arsenic fixation.

Arsenic fixation does not occur at a uniform rate in all soils, one soil showing an increase in fixation after 7 weeks, another showing very little after 18 hours.

Decreasing the moisture content of a soil below field capacity has no effect upon toxicity. This is apparently because, within the range of sublethal applications, the concentration of arsenic remains about the same in some soils and in others decreases.

Moisture content at field capacity is not an important factor in arsenic toxicity.

Curves of concentration, C, against application, A, may be constructed from two experimental determinations of concentration by the use of the equation

$$\log C = -\tfrac{3}{2} \log (F - x) + \log K.$$

Curves relating the percentage yield in the greenhouse tests to the concentration of soluble arsenic, plotted from the curves of C against A, were much more alike than the standard toxicity curves relating percentage yield to application of arsenic on the basis of dry soil—a fact suggesting that arsenic toxicity can be largely explained in terms of fixation.

ACKNOWLEDGMENTS

The authors extend thanks to Dr. J. P. Conrad, Dr. G. A. Baker, and other members of the Experiment Station staff who assisted in preparing the manuscript.

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TOXICITY STUDIES WITH SODIUM CHLORATE IN EIGHTY CALIFORNIA SOILS

A. S. CRAFTS

TOXICITY STUDIES WITH SODIUM CHLORATE IN EIGHTY CALIFORNIA SOILS[1]

A. S. CRAFTS[2]

INTRODUCTION

THE SUCCESSFUL USE of sodium chlorate as a herbicide in a region having such diverse soil and climatic conditions as California requires accurate knowledge of the relation of soil and climatic factors to its toxic action. Several publications have discussed the more important of these factors (*1–5, 8–9*)[3] and preliminary work on their relative importance has been reported (*3–5, 8–11, 13*).

For practical weed control with sodium chlorate, one needs a schedule of dosages to meet various field conditions. The principal difficulty in developing such a schedule is the many factors involved in the end result of chlorate application (*2*). Besides the initial toxicity[4] as determined primarily by nitrate concentration of the soil (*5*), leaching by rains and difference in susceptibility of weed species to chlorate are involved.

To solve the problems of chlorate toxicity, one must separate these several factors and determine the range through which each may be manipulated independently of the others. Only thus may all possible situations be anticipated and each factor properly adjusted. St. Johnswort (Klamath weed), for instance, on a sandy soil with an annual precipitation of 40 inches will require an entirely different treatment than hoary cress on clay soil in an arid region. In this field, obviously, the commercial concerns distributing sodium chlorate for herbicidal purposes have done little or nothing. Realizing the need for more accurate dosage recommendations, the writer collected 80 type soils of California, including most of the series important in agriculture. The effects of soil type and soil fertility upon chlorate toxicity in these soils were investigated. The relation between fertility and chlorate toxicity (*5*) revealed in these tests has been used as a basis for a proposed schedule of dosage that should prove useful wherever the chemical may be evenly distributed.

[1] Received for publication January 17, 1938.

[2] Assistant Professor of Botany and Assistant Botanist in the Experiment Station.

[3] Italic numbers in parentheses refer to "Literature Cited" at the end of this paper.

[4] The term "toxicity" has acquired a wide variety of meanings. For purposes of the present group of papers (*5, 7, 12*) the criterion adopted is the application of chemical causing an almost complete suppression of growth. This use of the word has developed because in the control of weeds the practical object is to inhibit development completely.

TABLE 1

TOXICITY OF SODIUM CHLORATE IN 4 CALIFORNIA SOILS, AS SHOWN BY GROWTH OF INDICATOR PLANTS*

Sodium chlorate expressed as p.p.m. $NaClO_3$ in air-dry soil	Yolo clay loam		Stockton adobe clay		Fresno sandy loam		Columbia fine sandy loam	
	Height	Fresh weight	Height	Fresh weight	Height	Fresh weight	Height	Fresh weight
Fifth run, harvested October 25, 1934								
p.p.m.	*cm*	*gm*	*cm*	*gm*	*cm*	*gm*	*cm*	*gm*
10	31	5.9	25	2.9	28	3.0	28	3.6
30	32	6.5	25	2.8	26	3.0	28	3.4
50	30	5.3	27	3.4	28	2.9	27	2.9
100	32	6.0	27	3.4	26	2.4	27	2.9
150	33	6.2	27	3.8	28	3.1	28	3.2
210	38	7.0	26	2.9	28	3.8	29	3.6
280	38	6.1	26	2.9	27	2.2	30	4.1
360	32	4.2	28	4.0	25	2.3	28	2.7
450	30	3.6	28	4.5	19	1.1	24	2.2
550	28	3.2	28	4.7	18	0.8	22	1.7
660	24	2.0	29	3.8	12	0.5	20	0.9
780	19	1.2	26	2.5	10	0.4	19	0.9
940	17	0.8	21	1.5	7	0.2	13	0.7
1,050	14	0.6	16	0.7	6	0.2	10	0.4
1,200	13	0.5	9	0.4	5	0.2	9	0.4
1,360	11	0.4	8	0.2	5	0.1	8	0.3
1,530	9	0.3	7	0.3	0	0.0	6	0.2
1,710	9	0.4	5	0.2	0	0.0	6	0.2
1,900	8	0.2	5	0.1	0	0.0	5	0.1
2,100	7	0.2	0	0.0	0	0.0	0	0.0
2,310	6	0.2	0	0.0	0	0.0	0	0.0
2,530	6	0.2	0	0.0	0	0.0	0	0.0
2,760	5	0.1	0	0.0	0	0.0	0	0.0
Check	30	5.7	25	3.1	24	2.5	24	2.6
Seventh run, harvested November 16, 1935								
p.p.m.	*cm*	*gm*	*cm*	*gm*	*cm*	*gm*	*cm*	*gm*
360	29	6.1	..	...	22	3.0	..	...
450	28	5.6	..	...	18	1.7	23	3.9
550	28	5.8	..	...	16	1.1	21	2.6
660	24	3.5	..	...	11	0.6	19	2.4
780	22	2.6	24	4.0	9	0.5	15	1.4
940	16	1.2	24	3.5	5	0.3	13	1.0
1,050	15	1.1	23	2.9	6	0.3	11	0.7
1,200	10	0.8	17	1.3	5	0.2	10	0.6
1,360	10	0.7	17	1.4	4	0.2	6	0.4
1,530	7	0.6	14	1.0	0	0.0	5	0.2
1,710	7	0.6	11	0.7	0	0.0	4	0.2
1,900	6	0.4	7	0.5	0	0.0	4	0.2
2,100	5	0.4	6	0.3	0	0.0	4	0.2
2,310	5	0.3	5	0.3	0	0.0	4	0.1
2,530	4	0.3	4	0.2	0	0.0	3	0.1
2,760	4	0.2	4	0.2	0	0.0	4	0.1
3,000	3	0.2	3	0.2	0	0.0	0	0.0
Check	23	3.9	18	2.6	21	2.9	21	3.3

* The check cultures represent the average of 20 replicates; all other values are the average of 5 replicates.

ADDITIONAL CROPS ON SOILS PREVIOUSLY TESTED

A previous publication (*4*) has discussed toxicity tests on 4 California soils, giving the data on the first 3 crops. This series was cropped four more times; and to complete the picture of the changes in toxicity that were revealed, table 1 has been prepared to show the results of the fifth and seventh crops. Values for the check cultures in this table represent the average of 20 replicates. All other values are the average of 5 replicates.

Considering all 7 runs, one sees that chlorate toxicity in the Stockton adobe clay, though highest at the beginning of the test, had dropped by the seventh run to a lower level than in the Yolo clay loam. The crop produced by the Stockton soil was, furthermore, consistently low. Although the initial toxicity seems related to the nitrate content of the soil (*5*), the loss in toxicity with time and cropping is caused by some soil factor apparently unrelated to fertility.

Toxicity in all 4 soils was lowered during these tests, and by the seventh run even that of the Fresno sandy loam had dropped to a value approximately that of the first run in the Yolo soil. By comparing points on the toxicity curve[5] for the first and seventh runs on these soils at the crop level of 1 gram, one finds the changes to be for Fresno sandy loam 150 to 560 p.p.m., or a difference of 410; for Columbia fine sandy loam 450 to 940 p.p.m., or a difference of 490; for Yolo clay loam 510 to 1,070 p.p.m., or a difference of 560; and for Stockton adobe clay 40 to 1,530 p.p.m., or a difference of 1,490. These are in the order of increasing clay content in these soils, but whether the changes are related to particle size or to some other property cannot be stated from these few tests.

EXPERIMENTAL METHODS ON EIGHTY SOILS

The soils and methods used in these tests have been described in detail in other papers (*4, 5*). The biological testing method developed through a series of stages from a simple technique involving single series of barley cultures in earthenware pots to a more carefully controlled practice with replication. One early concentration series is illustrated in figure 1. Concentrations of chlorate in these cultures, based on the air-dry weight of the soil, are 30, 120, 240, 375, 450, 600, and 900 p.p.m.

As these early tests soon showed the earthenware pots to be an uncontrolled factor, ordinary lacquered tin-plate cans were substituted. The No. 2 size of these cans holds 500 grams of most soils and is inexpensive

[5] Toxicity curves not published were constructed from table 1 and from table 9 of the earlier paper (*4*).

Fig. 1.— An early toxicity test with sodium chlorate in Yolo clay loam. Concentrations based on the air-dry soil are 30, 120, 240, 375, 450, 600, and 900 p.p.m. Barley was used as the indicator plant.

and convenient. Figure 2 shows a typical toxicity series in Ramada silt loam, an alluvial soil of intermediate texture and high fertility. In this series, concentrations from right to left are 0, 5, 15, 40, 80, 140, 220, 340, 490, and 680 p.p.m., based on the air-dry soil. This expanding series, developed after considerable experiment, has been used in the survey work reported in this and in an accompanying publication (7). As shown in the illustration, all tests were replicated three times.

Fig. 2.—A test series with sodium chlorate in Ramada silt loam. Concentrations, based on the air-dry soil, are 680, 490, 340, 220, 140, 80, 40, 15, 5, and 0 p.p.m. Three replicates.

TOXICITY RESULTS ON EIGHTY SOILS

During the development of the testing method the significance of results was considered. One of the first series set up in cans was a chlorate-toxicity test involving 15 concentrations and 2 checks, or 17 cultures per series. This test was replicated ten times and carried through 3 croppings. Data on the first crop (table 2) show how much variation may be expected between individual replicates at the various chlorate levels. The

average weight values in the last columns, if plotted, give a very smooth curve showing the relation between crop weight and chlorate concentration in the culture.

TABLE 2

TOXICITY OF SODIUM CHLORATE IN YOLO CLAY LOAM, AS SHOWN BY GROWTH OF INDICATOR PLANTS; 10 REPLICATIONS

(Harvested January 15, 1933)

Sodium chlorate expressed as p.p.m. $NaClO_3$ in air-dry soil	First replicate		Second replicate		Third replicate		Fourth replicate	
	Height	Fresh weight	Height	Fresh weight	Height	Fresh weight	Height	Fresh weight
p.p.m.	*cm*	*gm*	*cm*	*gm*	*cm*	*gm*	*cm*	*gm*
15	13.0	11.8	13.0	10.7	12.5	10.4	13.0	9.8
30	13.0	11.2	12.5	9.8	13.0	10.7	13.0	10.6
45	12.5	10.8	11.5	8.6	12.0	8.9	12.0	9.0
60	11.5	7.6	12.0	7.6	12.0	8.1	11.5	6.6
90	10.5	5.9	11.0	5.7	11.5	6.6	11.5	7.4
120	8.0	2.9	10.0	3.9	10.0	4.8	10.0	4.0
150	9.0	3.9	8.5	3.5	8.5	3.4	8.5	3.3
195	6.0	2.5	5.0	1.6	4.5	1.7	4.0	1.5
240	4.0	1.0	3.0	1.0	4.0	1.4	3.5	1.0
300	3.0	1.0	2.5	0.6	3.0	0.8	3.0	0.8
375	2.5	0.6	2.5	0.7	2.5	0.5	2.5	0.6
450	2.0	0.6	2.0	0.5	2.5	0.7	2.0	0.5
600	1.5	0.4	1.5	0.5	1.5	0.3	1.5	0.3
750	1.0	0.3	1.0	0.2	1.0	0.3	1.0	0.2
900	1.0	0.2	1.0	0.2	1.0	0.1	1.0	0.2
Check	13.0	10.5	13.0	10.1	12.0	10.3	13.5	11.5
Check	12.0	10.9	12.5	10.6	12.5	11.2	12.5	11.3

Sodium chlorate expressed as p.p.m. $NaClO_3$ in air-dry soil	Fifth replicate		Sixth replicate		Seventh replicate		Eighth replicate	
	Height	Fresh weight	Height	Fresh weight	Height	Fresh weight	Height	Fresh weight
p.p.m.	*cm*	*gm*	*cm*	*gm*	*cm*	*gm*	*cm*	*gm*
15	12.5	10.9	13.0	10.9	12.0	11.3	12.5	11.4
30	12.0	10.1	13.0	11.7	13.0	11.6	13.0	11.0
45	12.5	9.5	12.5	10.3	12.0	10.6	11.5	9.6
60	11.5	7.4	12.5	11.1	12.5	10.0	12.0	9.7
90	11.0	5.9	11.0	7.8	10.5	5.7	10.5	6.5
120	9.0	4.6	10.0	4.3	10.0	5.2	9.5	4.2
150	8.5	3.2	7.0	3.4	7.0	2.5	8.0	3.4
195	4.0	1.1	4.0	1.3	4.5	1.9	5.0	1.8
240	4.5	1.4	3.0	0.8	3.5	1.1	4.0	1.7
300	3.0	0.6	2.5	0.7	3.0	0.9	3.0	1.0
375	2.5	0.6	2.0	0.5	2.0	0.6	2.5	0.7
450	2.0	0.6	2.0	0.6	1.5	0.5	2.5	0.7
600	1.5	0.3	1.5	0.3	1.5	0.4	1.5	0.4
750	1.0	0.3	1.0	0.3	1.0	0.3	1.0	0.3
900	1.0	0.2	1.0	0.2	1.0	0.2	1.0	0.2
Check	13.0	11.0	13.0	11.4	13.5	11.7	13.0	11.2
Check	13.0	11.8	13.0	11.6	13.0	11.5	12.5	10.5

TABLE 2—(*Concluded*)

Sodium chlorate expressed as p.p.m. $NaClO_3$ in air-dry soil	Ninth replicate		Tenth replicate		Average		Average expressed as per cent of checks	
	Height	Fresh weight	Height	Fresh weight	Height	Fresh weight	Height	Fresh weight
p.p.m.	*cm*	*gm*	*cm*	*gm*	*cm*	*gm*	*per cent*	*per cent*
15	12.5	11.8	11.5	10.8	12.6	11.0	99.2	99.1
30	13.0	11.7	12.0	10.5	12.6	11.0	100.7	98.8
45	11.5	10.2	11.0	8.5	11.9	9.6	94.0	86.5
60	12.0	10.4	11.0	8.7	11.9	8.7	93.7	78.7
90	10.0	5.6	10.0	5.1	10.8	6.2	85.0	56.2
120	10.0	5.1	10.0	5.9	9.7	4.5	76.2	40.6
150	8.0	3.1	6.5	2.3	8.0	3.2	62.8	28.9
195	5.0	1.8	5.0	1.9	4.7	1.7	37.2	15.4
240	3.0	1.0	3.0	1.1	3.6	1.2	28.1	10.4
300	2.5	0.7	2.5	0.7	2.8	0.8	22.1	7.0
375	2.0	0.8	2.0	0.6	2.3	0.6	18.2	5.6
450	2.0	0.6	2.0	0.8	2.1	0.6	16.2	5.5
600	1.5	0.4	1.5	0.4	1.5	0.4	11.9	3.3
750	1.0	0.3	1.0	0.3	1.0	0.3	7.9	2.5
900	1.0	0.2	1.0	0.2	1.0	0.2	7.9	1.8
Check	12.5	11.3	12.0	12.1	12.8	11.1	101.5	100.3
Check	12.0	10.3	11.5	10.8	12.5	11.1	98.5	99.7

As too much work was involved in setting up and conducting tests involving this amount of replication, an attempt was made to reduce it by using only 5 replications. This arrangement was especially necessary because higher concentrations were needed if more than 1 cropping was to be used.

To ascertain the long-time behavior of arsenic, borax, and chlorate, series of tests using these chemicals in 4 California soils were established and have been reported—the borax results for 5 crops in a previous publication (*6*), the arsenic results for 7 crops in an accompanying paper (*7*), and the chlorate results in a previous paper (*4*) and in the present paper (table 1).

The early chlorate test indicated that crop production and toxicity were related, but with so few soils no generalization could be made. Consequently, chlorate tests were conducted on 80 type soils; and, with this number to judge from, the relation between high toxicity and low fertility became apparent. The soils used have been described in a companion paper (*7*). The technique was the same except that all chlorate tests included the 5 p.p.m. concentration and lacked that at 920 p.p.m.

Data on these tests, arranged in the order of increasing fertility as judged by crops on the untreated checks, are given in table 3. Where 2 or more series have the same crop weight in the checks, the ranking was determined by comparing total weights of the crops in the 3 check cul-

tures. In making up the averages reported, the figures in the second decimal place have been discarded, so that the averages lack the detail of the original totals. Where the totals were the same for 2 or more series, the soil with the highest toxicity, as indicated by the fewest surviving cultures, was placed first.

The relation of high toxicity to low fertility is apparent from table 3 and figure 3. That texture has no effect upon toxicity is evident. Without doubt, when other factors are constant, chlorate toxicity is largely determined by the fertility of the treated soil.

Among the apparent exceptions, No. 23, Rositas fine sand, No. 36, Superstition gravelly sand, No. 50, Meloland fine sandy loam, and No. 66, Imperial clay, attract attention. These soils are all from the Imperial Valley. Formed under arid conditions, they are high in salts, with sulfates, chlorides, and bicarbonates in abundance. Whereas nitrates are reported most effective in reducing chlorate absorption by plants, other anions are also involved; and these 4 soils apparently exemplify this fact. These anions hinder the absorption of chlorate and reduce toxicity without increasing crop production as does nitrate. No. 3, Dunnigan clay, and No. 10, Tulare clay, are 2 other soils moderately high in salts and very low in fertility. These 6 constitute the only serious exceptions to be noted in table 3.

The factors limiting the crop produced on a given sample of soil are numerous and varied. Besides fertility they include temperature, light, humidity, length of day, and combinations of these as related to the microbiological processes occurring in the culture. Since most of these factors were under little or no control in the greenhouse where the toxicity studies have been made, tests at different times and on different samples of the same soil vary appreciably. Table 4 presents data on tests at various dates on a number of soils. As in the accompanying paper (*7*) on arsenic, these results indicate the variations caused by lack of constant culture conditions and stress the desirability of running comparative tests on many soils at one time.

Since the relation between application and crop produced varies when tests are run under varying environmental conditions and when different samples of a given soil type are used, nitrate content or possibly total anion content might be a better criterion for judging chlorate dosage than is crop production. For practical purposes, however, the simple biological test is convenient where greenhouse facilities are available; and when comparisons are made simultaneously on all soils to be tested, the results seem reliable enough to determine relative dosages for application in the field.

TABLE 3

TOXICITY OF SODIUM CHLORATE IN 80 CALIFORNIA SOILS AS SHOWN BY GROWTH OF INDICATOR PLANTS

No.	Soil type	Date of harvest	Chlorate concentration—$NaClO_3$ in p.p.m. in air-dry soil									
			0	5	15	40	80	140	220	340	490	680
			Fresh weight of plants									
			gm	*gm*	*gm*	*gm*	*gm*	*gm*	*gm*	*gm*	*gm*	*gm*
1	Aiken clay loam	Dec. 26, 1935	0.5	0.3	0.1	0.1				*		
2	Pinole loam	Dec. 26, 1935	1.2	1.3	0.5	0.1	0.1					*
3	Dunnigan clay	July 26, 1934	1.2	1.1	0.8	0.5	0.2	0.1				
4	Merced adobe clay	Dec. 26, 1935	1.4	1.5	1.3	0.3	0.1					
5	*Conejo adobe clay*	*Dec. 26, 1935*	*1.4*	*1.3*	*0.5*	*0.1*						*
6	Niland gravelly sand	May 15, 1935	1.4	1.2	0.6	0.5	0.3				*	
7	*Aiken gravelly loam*	*Feb. 2, 1935*	1.5	0.6	0.2	0.1			*			
8	Alamo adobe clay	Dec. 26, 1935	1.5	1.4	0.8	0.3	0.2					
9	Anita adobe clay	Dec. 26, 1935	1.6	1.5	0.6	0.1	0.1					
10	Tulare clay	Dec. 26, 1935	1.6	1.7	0.7	0.3	0.2	0.1				
11	Oakley sand	Dec. 26, 1935	1.7	0.9	0.4	0.1				*		
12	*Corning gravelly loam*	*Feb. 1, 1935*	*1.7*	*1.3*	*0.4*	*0.1*			*			
13	Fresno light clay	Dec. 26, 1935	1.7	1.0	0.5	0.1				*		
14	Yolo adobe clay	Dec. 26, 1935	1.8	1.2	0.4	0.2						
15	Tulare fine sandy loam	Dec. 26, 1935	1.8	1.2	0.6	0.2	0.1				*	
16	Tujunga sand	May 15, 1935	1.8	1.3	0.4	0.2	0.1				*	
17	*Montezuma adobe clay*	*Dec. 26, 1935*	*1.8*	*1.5*	*0.5*	*0.2*	*0.1*					
18	Clear Lake adobe clay	May 15, 1935	1.8	1.5	0.4	0.1	0.1					*
19	*Farwell adobe clay*	*Dec. 26, 1935*	*1.8*	*1.4*	*0.6*	*0.3*	*0.1*					*
20	Madera clay	Dec. 26, 1935	1.9	1.6	0.7	0.2	0.1					
21	Gridley loam	Dec. 26, 1935	1.9	1.6	0.8	0.4	0.1	0.1			*	
22	Landlow adobe clay	Dec. 26, 1935	1.9	2.0	1.5	0.5	0.2	0.1				
23	Rositas fine sand	May 15, 1935	2.0	1.8	1.0	0.8	0.4	0.2	0.2	0.1		
24	*Sierra gravelly loam*	*Feb. 2, 1935*	*2.1*	*2.1*	*1.2*	*0.2*	*0.1*	*0.1*			*	
25	Arbuckle clay loam	Aug. 19, 1934	2.1	1.9	1.0	0.3	0.2	0.1			*	
26	Panoche light loam	Dec. 26, 1935	2.1	1.7	0.7	0.3	0.1				*	
27	Diablo adobe clay	Dec. 26, 1935	2.2	2.0	1.2	0.4	0.2					
28	Stockton adobe clay	May 15, 1935	2.3	2.3	1.7	0.8	0.3	0.2	0.1			
29	Mariposa silt loam	Feb. 1, 1935	2.3	2.2	1.9	0.2	0.1	0.1				
30	Vina loam	Dec. 26, 1935	2.4	2.1	1.7	0.6	0.2	0.1				*
31	*Willows adobe clay*	*Feb. 2, 1935*	*2.5*	*1.8*	*1.0*	*0.2*	*0.1*				*	
32	Oakdale coarse sandy loam	Dec. 26, 1935	2.5	2.3	2.0	0.7	0.2	0.1				*
33	Tehama loam	Dec. 26, 1935	2.6	2.2	1.6	0.3	0.1				*	
34	Chino silty clay loam	May 17, 1935	2.6	2.3	1.3	0.7	0.4	0.2	0.1			
35	Holland loamy gravelly sand	Feb. 1, 1935	2.6	2.0	1.5	0.4	0.2	0.1		*		
36	Superstition gravelly sand	May 17, 1935	2.6	2.3	1.5	1.0	0.8	0.6	0.3	0.1		*
37	Marvin silty clay loam	Dec. 26, 1935	2.7	2.7	2.4	0.8	0.3	0.1				
38	Sites adobe clay	Feb. 1, 1935	2.8	3.0	2.3	0.5	0.3	0.1			*	
39	Salinas clay	Dec. 26, 1935	2.8	2.3	1.1	0.7	0.4	0.1				
40	*Placentia light loam*	*May 15, 1935*	*2.8*	*2.4*	*1.4*	*0.8*	*0.4*	*0.1*			*	
41	Foster fine sandy loam	Dec. 26, 1935	3.0	2.3	1.4	0.7	0.2	0.1				
42	Greenfield coarse sandy loam	Dec. 26, 1935	3.0	2.7	1.1	0.4	0.1	0.1				*

* Germination of seeds prevented at this and all higher concentrations. Fresh weight of plants i cultures between reported weight and point of no germination was less than 0.1 gram.

TABLE 3—(*Concluded*)

No.	Soil type	Date of harvest	Chlorate concentration—$NaClO_3$ in p.p.m. in air-dry soil									
			0	5	15	40	80	140	220	340	490	680
			Fresh weight of plants									
			gm	*gm*	*gm*	*gm*	*gm*	*gm*	*gm*	*gm*	*gm*	*gm*
43	Porterville adobe clay	Dec. 26, 1935	3.0	2.8	1.9	0.7	0.4	0.1	0.1			
44	Rocklin sandy loam	Feb. 2, 1935	3.0	2.8	2.0	0.4	0.2	0.1	0.1			*
45	Salinas fine sandy loam	Dec. 26, 1935	3.0	2.9	2.4	0.5	0.3	0.1				
46	Hanford fine sandy loam	Dec. 26, 1935	3.1	2.4	1.3	0.7	0.4	0.2	0.1			
47	Montezuma adobe clay	May 15, 1935	3.1	3.1	2.6	0.9	0.4	0.2				*
48	Honcut loam	Dec. 26, 1935	3.1	3.2	3.0	1.4	0.4	0.2	0.1			
49	Redding gravelly loam	Jan. 11, 1936	3.2	2.7	2.7	1.3	0.4	0.1				*
50	Meloland fine sandy loam	May 17, 1935	3.2	3.3	3.2	2.4	2.1	1.6	1.1	0.9	0.5	0.4
51	Ramona sandy loam	May 17, 1935	3.3	3.2	1.6	1.0	0.6	0.3	0.1		*	
52	Antioch clay loam	Dec. 26, 1935	3.3	3.5	3.2	1.5	0.6	0.3	0.1			
53	Merced fine sandy loam	Dec. 26, 1935	3.6	3.6	2.4	0.8	0.3	0.2				
54	Yolo loam	Feb. 1, 1935	3.7	3.5	3.2	0.9	0.4	0.1			*	
55	Delano fine sandy loam	Dec. 26, 1935	3.7	3.4	3.3	1.6	0.5	0.3	0.1			
56	Pleasanton loam	Dec. 26, 1935	3.8	4.0	3.5	1.9	0.7	0.4	0.2			
57	Hanford sandy loam	Dec. 26, 1935	3.9	3.4	2.3	1.2	0.5	0.2	0.1	0.1		
58	Madera loam	May 17, 1935	3.9	3.8	3.3	1.4	0.4	0.1			*	
59	Yolo fine sandy loam	Feb. 1, 1935	3.9	4.1	3.9	1.0	0.5	0.1			*	
60	Fresno sandy loam	May 15, 1935	4.0	3.9	3.1	2.5	1.3	0.7	0.3	0.1		*
61	Yolo clay	Feb. 1, 1935	4.1	4.0	3.9	1.3	0.5	0.1				
62	Arbuckle gravelly sandy loam	Feb. 2, 1935	4.1	4.3	4.0	1.9	0.7	0.2	0.1	0.1		
63	San Joaquin loam	May 17, 1935	4.1	3.9	3.4	1.3	1.0	0.5	0.2	0.1		
64	Chualar fine sandy loam	Dec. 26, 1935	4.1	3.8	3.3	1.4	0.5	0.2				
65	Dublin adobe clay	Dec. 26, 1935	4.1	3.5	2.4	1.1	0.7	0.4	0.2	0.1	0.1	*
66	Imperial clay	May 17, 1935	4.3	4.4	3.6	1.9	1.2	0.9	0.6	0.4	0.2	0.1
67	Sierra sandy loam	Feb. 2, 1935	4.4	4.6	3.9	1.6	0.4	0.1			*	
68	Capay adobe clay	Feb. 1, 1935	4.5	4.7	4.5	0.9	0.2	0.1			*	
69	Esparto clay	Feb. 1, 1935	5.4	5.8	6.3	3.0	1.0	0.2	0.1			
70	Sites fine sandy loam	Feb. 2, 1935	5.6	6.1	5.6	3.8	1.5	0.4	0.1	0.1		*
71	Farwell loam	Dec. 26, 1935	5.6	5.5	5.3	3.2	1.2	0.3	0.1			
72	Ramada silt loam	Dec. 26, 1935	5.7	5.8	4.8	3.2	1.5	0.7	0.2	0.1		
73	Egbert loam	May 15, 1935	6.2	6.0	5.9	5.0	4.6	3.2	1.4	0.7	0.4	0.1
74	Columbia silty clay loam	May 17, 1935	6.5	6.8	7.3	5.7	4.0	2.1	1.2	0.7	0.5	0.2
75	Panoche adobe clay	Dec. 26, 1935	6.9	6.2	5.5	4.0	2.5	1.2	0.8	0.4	0.3	0.1
76	Columbia fine sandy loam	May 15, 1935	7.8	7.5	7.8	6.0	3.8	2.6	1.8	1.1	0.7	0.3
77	Sacramento clay loam	May 15, 1935	7.9	7.3	7.7	6.1	3.2	2.1	0.9	0.5	0.2	0.1
78	Yolo silt loam	Feb. 1, 1935	8.8	8.3	8.3	8.4	7.1	4.9	3.3	0.9	0.6	0.2
79	Yolo clay loam	Feb. 1, 1935	9.2	8.8	9.6	8.6	6.4	1.5	1.1	0.5	0.3	0.1
80	Yolo clay loam	May 15, 1935	11.2	12.0	11.8	9.4	7.1	4.7	2.9	1.4	0.8	0.4

* Germination of seeds prevented at this and all higher concentrations. Fresh weight of plants in cultures between reported weight and point of no germination was less than 0.1 gram.

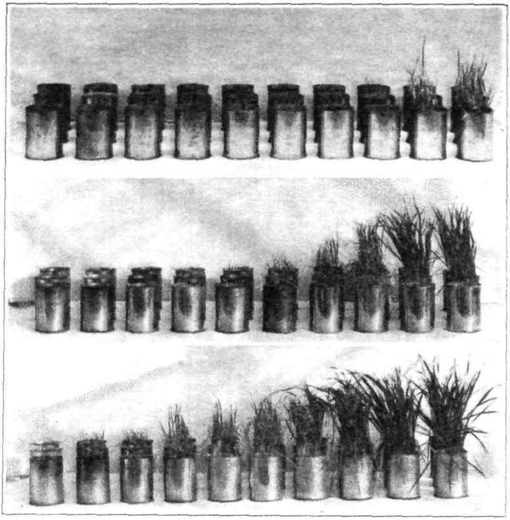

Fig. 3.—Test series with sodium chlorate in Aiken gravelly loam, Hanford sandy loam, and Panoche adobe clay. Concentrations run from 680 to 5 p.p.m. $NaClO_3$ with check cultures on the extreme right. Three replicates. Toxicity is closely correlated with fertility and is unaffected by texture.

DISCUSSION

To use sodium chlorate in weed control in semiarid regions one must know, among other things, the relative influence of its vertical distribution in the soil, and the comparative susceptibility of the plant species involved. Distribution, as previously explained (*2, 3, 4, 11*), depends largely upon leaching and is related both to precipitation and to soil type. Susceptibility in the practical sense includes: first, tolerance of the toxic action of the herbicide and, second, root distribution as related to penetration of the chemical into the soil.

How rainfall and soil type affect distribution of chlorate in the soil has been indicated (*2, 3, 4, 11*). With the extreme variations that occur in soil

TABLE 4

COMPARATIVE RESULTS OF TOXICITY TESTS ON REPEATED RUNS WITH SODIUM CHLORATE IN 6 CALIFORNIA SOILS

Soil type	Run No.	Date of harvest	Chlorate concentration—$NaClO_3$ in p.p.m. in air-dry soil									
			0	5	15	40	80	140	220	340	490	680
			Fresh weight of plants									
			gm	*gm*	*gm*	*gm*	*gm*	*gm*	*gm*	*gm*	*gm*	*gm*
Arbuckle clay loam	1*	Feb. 1, 1935	2.1	1.7	0.7	0.1	0.1					
	2†	Aug. 19, 1934	2.1	1.9	1.0	0.3	0.2	0.1				
	3‡	Dec. 4, 1936	3.6	3.4	2.3	0.4	0.1	0.1				
	4§	Feb. 17, 1936	4.4	4.8	6.6	0.9	0.5	0.1	0.1			
Columbia fine sandy loam	1†	May 15, 1935	7.8	7.5	7.8	6.0	3.8	2.6	1.8	1.1	0.7	0.3
	2‡	Nov. 26, 1936	8.8	9.2	9.1	8.1	5.2	2.2	0.7	0.1		
	3¶	Dec. 7, 1933	9.2	9.1	8.8	7.3	5.5	3.5	2.4	1.9	0.9	0.4
	4§	Feb. 17, 1936	11.4	11.0	10.4	8.8	6.5	4.4	4.1	1.0	0.6	0.1
Fresno sandy loam	1‡	Nov. 26, 1936	3.4	3.3	2.9	1.4	0.4	0.1	0.1			
	2†	May 15, 1935	4.0	3.9	3.1	2.5	1.3	0.7	0.3	0.1		
	3¶	Dec. 7, 1933	6.0	5.1	3.9	2.8	2.3	1.2	0.4	0.2	0.1	
	4§	Feb. 17, 1936	7.9	8.4	8.3	6.0	3.3	1.8	0.5			
Stockton adobe clay	1‡	Nov. 26, 1936	2.2	1.6	1.1	0.3	0.1					
	2¶	Dec. 7, 1933	2.3	2.2	1.9	1.0	0.5	0.1	0.1			
	3†	May 15, 1935	2.3	2.3	1.7	0.8	0.3	0.2	0.1			
	4§	Feb. 17, 1936	5.5	5.0	4.0	1.4	0.4	0.1	0.1			
Yolo fine sandy loam	1*	Aug. 19, 1934	3.6	3.0	1.7	0.7	0.4	0.2	0.1			
	2†	Feb. 1, 1935	3.9	4.1	3.9	1.0	0.5	0.1				
	3§	Feb. 17, 1936	5.6	5.6	4.8	4.9	3.2	1.1	0.1	0.1		
	4‡	Dec. 4, 1936	7.7	6.7	5.7	3.2	1.4	0.7	0.3	0.1		
Yolo clay loam	1†	Feb. 1, 1935	9.2	8.8	9.6	8.6	6.4	1.5	1.1	0.5	0.3	0.1
	2‡	Nov. 26, 1936	9.3	6.6	6.1	4.0	2.9	1.7	0.9	0.3	0.2	0.1
	3‖	Oct. 29, 1932	9.7	11.0	11.3	11.0	9.8	7.9	5.5	3.3	2.3	1.0
	4*	Aug. 19, 1934	11.0	10.1	8.9	6.7	4.4	2.6	1.2	0.7	0.3	0.2
	5¶	Dec. 7, 1933	11.1	10.7	9.5	7.8	6.0	4.6	3.8	1.8	1.2	0.2
	6**	Jan. 15, 1933	11.1	11.0	11.0	10.0	7.0	3.6	1.4	0.7	0.5	0.3
	7†	May 15, 1935	11.2	12.0	11.8	9.4	7.1	4.7	2.9	1.4	0.8	0.4
	8§	Feb. 17, 1936	17.0	17.4	16.5	11.3	9.1	4.9	2.6	0.9	0.3	0.1

* Repeat run standard check series.

† From table 3.

‡ Chemical nutrient series, from Crafts (*5*).

§ Nutrient series, from Crafts (*5*).

¶ By interpolation from Crafts (*4*, table 9).

‖ By interpolation from Crafts (*4*, table 1).

** By interpolation from table 2.

profiles and in the distribution of precipitation, exact recommendations are difficult to formulate, and local experience based upon empirical tests and field observation is essential to successful practice.

Plant susceptibility cannot easily be put on a comparative basis because it is hard to grow a wide variety of weed species simultaneously under constant culture conditions. Some work of this type has been done

(3, 8, 13), however, and more is contemplated. Collection of information is largely a matter of methods; and, as these are developed, all common weed species will be tested. The most valuable generalization coming from work thus far is that plants native to arid regions seem to tolerate more chlorate than plants of humid climates.

For any given plant, toxicity of chlorate seems to depend largely upon the numbers and kinds of anions in the culture medium. In leached soils, nitrate effects far overshadow those of other anions *(5)*. In arid regions chlorides, sulfates, and bicarbonates enter the problem; and in these soils, probably, conductivity and nitrate content of soil extracts might be combined to provide a toxicity index. Perhaps, eventually, simple tests for nitrates and total salts will provide adequate information for formulating chlorate dosages.

Meanwhile an attempt will be made to draw up a schedule for the 80 soils that have been tested. At the outset, using field experience and the results of many plot tests, a basic scale of dosages adequate for controlling weeds that yield readily to chlorate is suggested. Such weeds are St. Johnswort, morning-glory, Russian knapweed, Canada thistle, and Johnson grass. Adequate penetration into the soil as determined by rainfall and soil type is assumed, and application should be made at such a time that decomposition of the chlorate is minimized. Under these conditions the soils of table 3, in which chlorate application up to 80 p.p.m. prohibited growth, should receive 1 pound per square rod. Those limiting growth at 140 p.p.m. should receive 2 pounds; at 220 p.p.m., 3 pounds; at 340 p.p.m., 4 pounds; at 490 p.p.m., 6 pounds; at 680 p.p.m., 8 pounds.

Under ideal conditions, of course, these dosages might be reduced even to one-half the values given. Under average conditions, this schedule is necessary. Against hoary cress, Bermuda grass, camel thorn, and white horse nettle this basic dosage should be doubled. Other common perennials range somewhere between these limits.

To workers versed in soil characteristics, one fact is apparent: though tests of the type in table 3 give a broad view of chlorate toxicity because this response is related to fertility, any generalized application of the dosage schedule may fail in many specific cases because fertility may vary so widely within a soil type. Numerous factors such as previous treatment, organic matter content, microflora, and the inevitable variations in deposition inherent in alluvial soils particularly, all tend to cause differences in fertility. Given such difficulties, one criterion may often prove useful in determining dosage in the field: the relative development of weeds or of crops in different localities at any given time is

often the best available measure of fertility, and a casual survey of plant growth always helps in determining application rate of chlorate.

The chlorate dosages necessary on certain soils and against some weeds are not only too expensive but harmful to the soils. When dosage exceeds 8 pounds per square rod, the cost approaches that of carbon bisulfide. On agricultural areas, considering the time lost through the residual sterility from chlorate and the undesirability of introducing sodium into the replaceable base complex, it seems advisable to use carbon bisulfide and return the land rapidly to crop production. But on waste areas, where permanence is to be desired, especially if deep-rooted perennials occur, chlorate is the logical herbicide in all cases.

As these studies emphasize, there are situations where chlorate is the best herbicide, other situations where carbon bisulfide is preferable and, as an accompanying paper (*7*) points out, some conditions favor the use of arsenic. One should not forget that in weed control numerous reagents have proved effective. In a comprehensive plan, all these should be used. The field operator should familiarize himself with the various methods and their limitations and should use each reagent to maximum advantage in the situation to which it is adapted.

SUMMARY

Repeated cropping of chlorate-treated soils resulted in continued loss of toxicity. Toxicity to the first crop (*4*) was highest in Stockton adobe clay, second in Fresno sandy loam, third in Columbia fine sandy loam, and lowest in Yolo clay loam. By the seventh crop toxicities had shifted so that Fresno sandy loam stood highest, Columbia fine sandy loam second, Yolo clay loam third, and Stockton adobe clay lowest. Although fertility largely governs the initial toxicity of chlorate in soils (*5*), some other factor controls the change in toxicity with time and cropping.

The toxicity-testing method used in studies reported here and in previous papers has been developed from a simple concentration series with barley in earthenware pots to the present technique using oats in replicated series in No. 2 cans. A test with 10 replicates gave excellent results but proved labor-consuming and slow.

Using a simplified technique with 10 concentrations replicated three times, 80 agricultural soils of California were tested for initial toxicity when treated with sodium chlorate.

The general relation of toxicity to fertility (*5*) was confirmed. In nearly every case, soils deviating markedly from the expected results proved to have come from arid regions and consequently to be high in total salts.

Repeated tests on a given soil type conducted at different times vary in the toxicities shown and reveal less correlation between toxicity and fertility than do the series run in large numbers for comparative purposes (table 3). For this reason, soils to be compared should be tested simultaneously.

Leaching and species susceptibility are known to affect chlorate toxicity. Under average field conditions a schedule of dosages of from 1 to 8 pounds per square rod should control susceptible species effectively, the dosages between these limits being fixed by the fertility of the soil. Under ideal conditions this schedule might be reduced. Under average conditions and against resistant species it should be doubled.

When chlorate dosage runs above 8 pounds per square rod, the cost approaches that of carbon bisulfide. Considering the loss of crops and the undesirability of introducing sodium into the replaceable base complex, carbon bisulfide seems preferable under these conditions.

Several chemicals, including arsenic, chlorate, and carbon bisulfide, have proved useful in weed control. In a comprehensive program all should be used, each under the conditions where it is most effective and economical.

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